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AN EXPERIMENTAL STUDY OF MEASURING
OSCILLATORY AND TRANSIENT PRESSURE
IN HYDRAULIC SYSTEMS

THESIS

AFIT/GAE/AA/78D-9 Shraga Katz
Major IAF

Approved for public release; distribution unlimited.

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AN EXPERIMENTAL STUDY OF MEASURING OSCILLATORY AND TRANSIENT PRESSURES IN HYDRAULIC SYSTEMS.

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
In Partial Fulfillment of the
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Master of Science

by

Shraga Katz, B.S.C.

Major IAF

Graduate Aeronautical Engineering

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Preface

This study is concerned with a comparison between two methods of measuring transient and oscillatory pressures in aircraft hydraulic systems. One method utilizes a standard fluid line transducer (in-line), while the other method uses a transducer clamped to the outside of the line (clamp-on).

My initial intention was to investigate dynamic properties of new hydraulic fluids. I was basically interested in oscillatory pressures and flows. This investigation made use of the two measuring methods mentioned above. After preliminary work was done, using a frequency response computer program named HSFR, it was realized that the differences between the various fluid's properties as predicted by the program were relatively small. Previous work showed that there are differences between simultaneous pressure measurements obtained by the two transducers, in the same order of magnitude as the differences in the pressures of the various fluids, as predicted by HSFR. In this case, I had to determine which measuring method is more accurate in order to use it in such an investigation. This by itself implied a new study.

During the investigation some interesting points were raised concerning the frequency response program, and they will be discussed in this study.

I wish to express my sincere appreciation to Professor

M.E. Franke, my thesis adivsor, who shared in this research by offering valuable comments and advice. I would also like to thank Mr. K.E. Binnes and Mr. P.D. Lindquist. Their expertise in computer programming and hydraulic system operation and response were invaluable in my study.

I wish to express my sincerest thanks to Mr. H. Lee of the Power Division of Air Force Propulsion Laboratory. His knowledge of hardware and design requirements, and his patience were of great help in my work.

Finally, I wish to thank my wife, Chava, for patience and encouragement. Without her help this study could not have been possible.

Shraga Katz

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List of Symbols

Symbol	Definition
E	Modulus of Elasticity
HSFR	Hydraulic Systems Frequency Response
I	Moment of Inertia
ℓ	Length
M	Mass
P	Pressure
RPM	Revolutions per Minute
$\overline{V}$	Volts
V	Velocity of Fluid
ΔP	Change in Pressure
ΔV	Change in Volume
ρ	Fluid Density per Unit Length

Abstract

This study is concerned with two basic techniques for measuring oscillatory and transient hydraulic pressures: use of a standard fluid line transducer (in-line) and a transducer clamped to the outside of the line (clamp-on).

Both transducers were installed in a laboratory hydraulic system side by side. Several sets of runs were made under various conditions. Measurements taken indicated deviations between the two transducers as high as $\pm$ 20%. The clamp-on transducer was affected by the line vibrations and should be used in a hydraulic system with some limitations.

The experimental measurements were compared with the theoretical results from a frequency response computer program. The measured oscillatory pressures were up to 30% greater than those predicted by the computer program.

I. Introduction

Background

Many hydraulic systems used in present day engineering applications involve lines or pipes of considerable length. Pumps which transmit fluid through hydraulic lines under high pressure, import periodic pulses to the fluid which can induce undesirable vibrations, and create serious problems in aircraft or ground systems. These pulses in the fluid cause internal forcing functions which vibrate the line and transmit loads into supporting structure.

Many theoretical and experimental investigations have been conducted in order to predict the performance of systems when they are subjected to disturbances in fluid pressure and flow. A significant contribution was made by McDonnell Douglas Corporation by developing and verifying four computer programs used to simulate hydraulic systems under dynamic conditions. One of these computer programs that was of interest in this study was the Hydraulic Systems Frequency Response (HSFR).

HSFR program predicts how oscillatory flows and pressures caused by the acoustical energy content of a pump output are transmitted through the lines and components of hydraulic systems. The program predicts the pump speeds at which major resonances occur, and defines the amplitude and location of the oscillatory pressure, flow and the standing waves patterns (Ref 1 and 2).

The experiments in the hydraulic systems require pressure measurements of oscillatory and transient pressures. This study considered two basic techniques for measuring these pressures. One technique utilized a standard fluid line transducer (in-line), while the second technique used a transducer clamped to the outside of the line (clamp-on). The pump was the source of oscillatory pressures. These pulsations were measured by the in-line and clamp-on transducers.

The in-line transducer method requires installing the transducer in the system with standard or special hydraulic fittings. This pressure transducer is usually flush mounted with the pipe inner surface. The pressure fluctuation acts directly on the transducer. The output of the transducer is voltage proportional to the pressure. Sometimes the configuration of the systems causes difficulties in selecting the locations of the fittings for the in-line transducers. That led to interest in using a clamp transducer that is clamped to the outside of the line. This transducer responds to the pressure induced radial expansion of the line. The sensitivity is dependent on the line diameter, wall thickness, material, clamping force and preload of the transducer. Using this method, it is possible to move the transducer to different places without disturbing the system or losing any fluid.

Objective

The purpose of this study was to compare the response in-line transducer and the clamp-on transducer, to find if there are limitations in using one of these methods and to compare between the transducer pressure measurements and the predicted values from HSFR.

Scope

In order to make the comparison, both pressure transducers were installed in a laboratory hydraulic system which consisted of a long line with a hydraulic pump at one end of the line and a pressure relief surge valve at the other end. The system was designed with possibilities for clamping and unclamping the line in order to investigate the influence of the vibrations on the accuracy of the measurements. Several sets of runs were made for different conditons. The experimental measurements were also compared with HSFR output plots of the peak pressure.

II. Experimental Apparatus

Figure 1 shows a schematic diagram of the laboratory hydraulic system experimental set-up.

Test Line

The line used in the experiments was a 0.625 in. outside diameter stainless steel tube with a 0.065 in. wall thickness. Its length was 334.5 in. from the pump outlet to the load valve. This tube was supported by clamping to an "I" beam at 10 to 20 in. intervals by thick aluminum clamps.

Special hydraulic fittings were inserted in three places along the line to permit installation of the in-line transducers. The locations were 44.4, 168.7, 313.5 in. from the pump as shown in Fig 1.

The line was connected to the pump in two different ways:

a. With a hose 0.75 in. I.D. and 50 in. length. See Appendix A for the bulk modulus.

b. With a tube with the same dimensions as the line, and 41 in. length.

The Pump

The pump was a constant pressure variable displacement, manufactured by ABEX and known as an F-4 pump. It was driven by a variable driven unit of 15 HP over a speed range of 1200 to 5500 rpm.

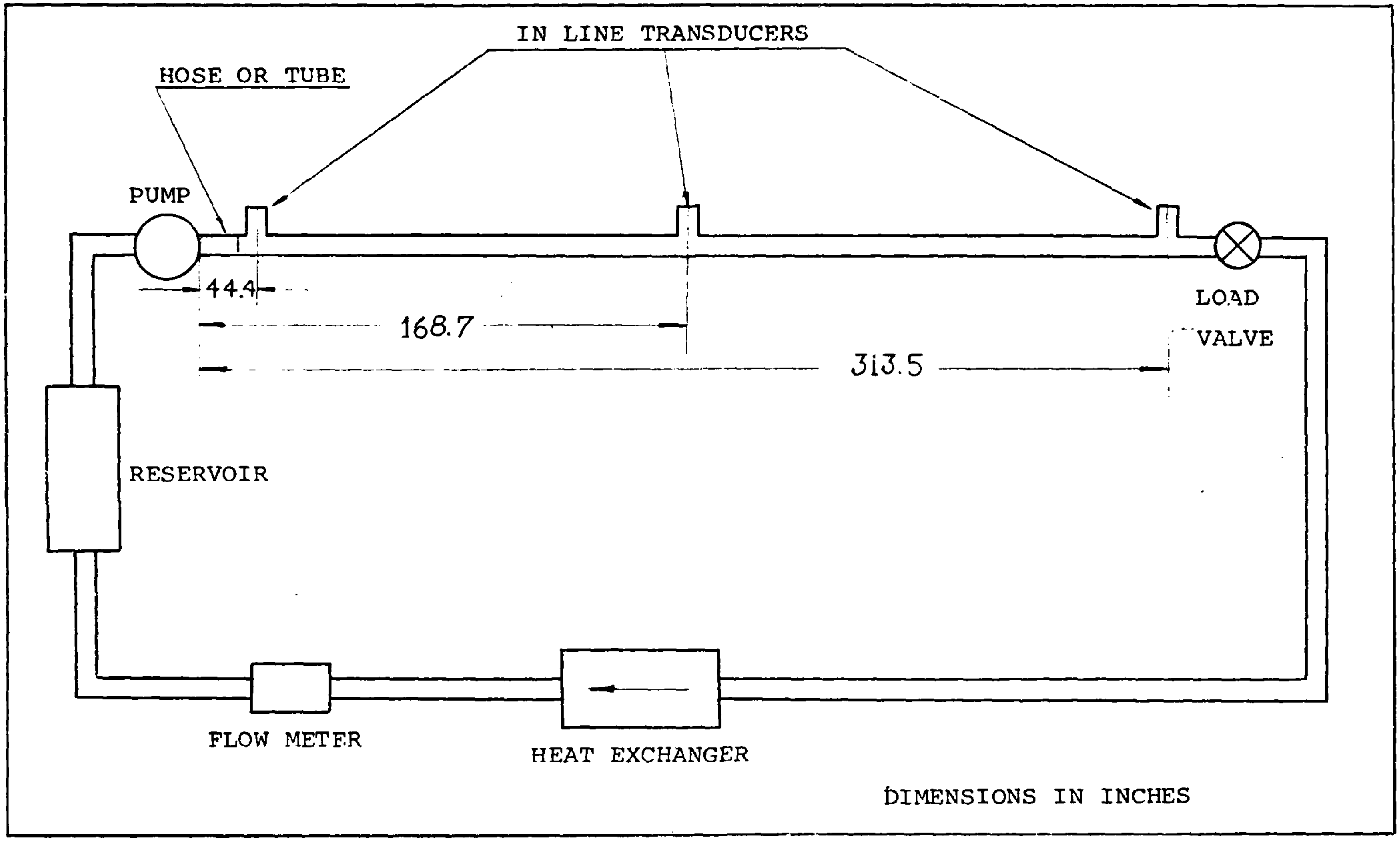

Figure. 1. Schematic Diagram of Experimental Setup

In-Line Transducers

The in-line transducer was Stathan thin film strain gauge transducer with a range of 0 to 5000 psia and natural frequency of 70000 Hz in air. The best that it could be calibrated to was $\pm$ 20 psi.

With a strain gauge pressure transducer, a pressure change is converted into a change in resistance caused by the strain in a strain gauge. The output from the transducer is voltage that can be measured after amplification by a voltage measuring instrument.

Clamp-On Transducer

The clamp-on transducer that was used in the system to measure the oscillatory pressures, was a Kistler Type 205 H2 piezoelectric transducer. It had a maximum pressure dynamic range of 10000 psi and a sensitivity of about 0.5 volts per 1000 psi. When a piezoelectric element is stressed mechanically, its dimensions change and it generates an electric charge. If the electrodes are not short circuited, a voltage associated with the charge appears. The voltage is measured by a voltage measuring instrument.

Piezoelectricity is defined as an electrical polarization produced by mechanical strain in crystals. The polarization being proportioned to the strain and changing sign with it.

Two different clamps were used for the clamp-on transducer as shown in Appendix D: the original one with a

circular hole, Fig D-1a and a modified one with a square hole, Fig D-1b.

Spectrum Analyzer

The spectrum analyzer that was used in the experiments was a Nicolet Scientific Corporation Model 444, a Fast Fourier Transform (FFT) computing analyzer. The advantage of using a spectrum analyzer is that this is an instrument which decomposes a signal into the frequency components. Many complex signals are difficult to understand as time functions, however, their spectra - the display of energy versus frequency - are relatively easy to understand.

In these experiments, the spectrum analyzer measured the frequency spectrum of the fluctuating pressure. Averaging of 32 such spectra was done in 6.4 seconds in order to approach the average values.

III. Experimental Procedures

Calibration Procedures

The in-line pressure transducers were calibrated statically prior to the test runs with a dead weight tester in a separate set-up.

The clamp-on pressure transducer calibration was accomplished before each run, because its sensitivity depends on the pipe wall thickness, pipe diameter, material and clamping force, all of which vary along a length of pipe due to the tolerances.

The initial installation of the sensing element transducer in the clamp requires special care. The sensing element is interchangeable among different clamps for different tube diameters. To allow for dimensional changes, shims are used under the sensing element boss to adjust the amount of preload between the element and the line. In use, the sensing element was preloaded against the pipe to give an output approximately 2.2 volts when both the clamp and the element were fully torqued down (2-4 ft lbs). (Ref 12) is a manual for using the clamp-on transducer.

The line was heated to the average test temperature (105°F) prior to the calibration by operating the pump for several minutes.

The system was pressurized constantly with 25 psig in the return line. The voltage corresponded to the steady state pressure (approximately 2950 psig).

The clamp-on transducer was calibrated by dividing the difference in the voltages to the difference in the pressures that were corresponded to those voltages.

$$\text{Calibration} = \frac{\overline{V}(2950 \text{ psig}) - \overline{V}(25 \text{ psig})}{2950 \text{ psig} - 25 \text{ psig}} \qquad (1)$$

In the DC mode, the transducer has a time constant of 1500 seconds, so when the start up and steady state voltage outputs are taken, it is essential that it be done quickly, otherwise the voltage output will decay and reduce the accuracy of the calibration.

The calibration procedure was repeated at the end of the test and the average values for the calibration were used in the calculations. Figure 2 shows a typical calibration curve obtained by plotting the DC output versus the output of a Kistler pressure transducer. The pressure was varied with a hydraulic hand pump.

Test Procedures

The hydraulic system was operated initially with the pump speed set at 4500 rpm and the fluid flow adjusted to the desired mean value. The system was allowed to run undisturbed while a steady fluid temperature was reached. The output voltages of the in-line and clamp-on transducers were measured with the spectrum analyzer. Additional measurements were made by decreasing the pump speed by 50 or 100 rpm in order to change the input frequency, and repeating transducers voltage measurements. Data were

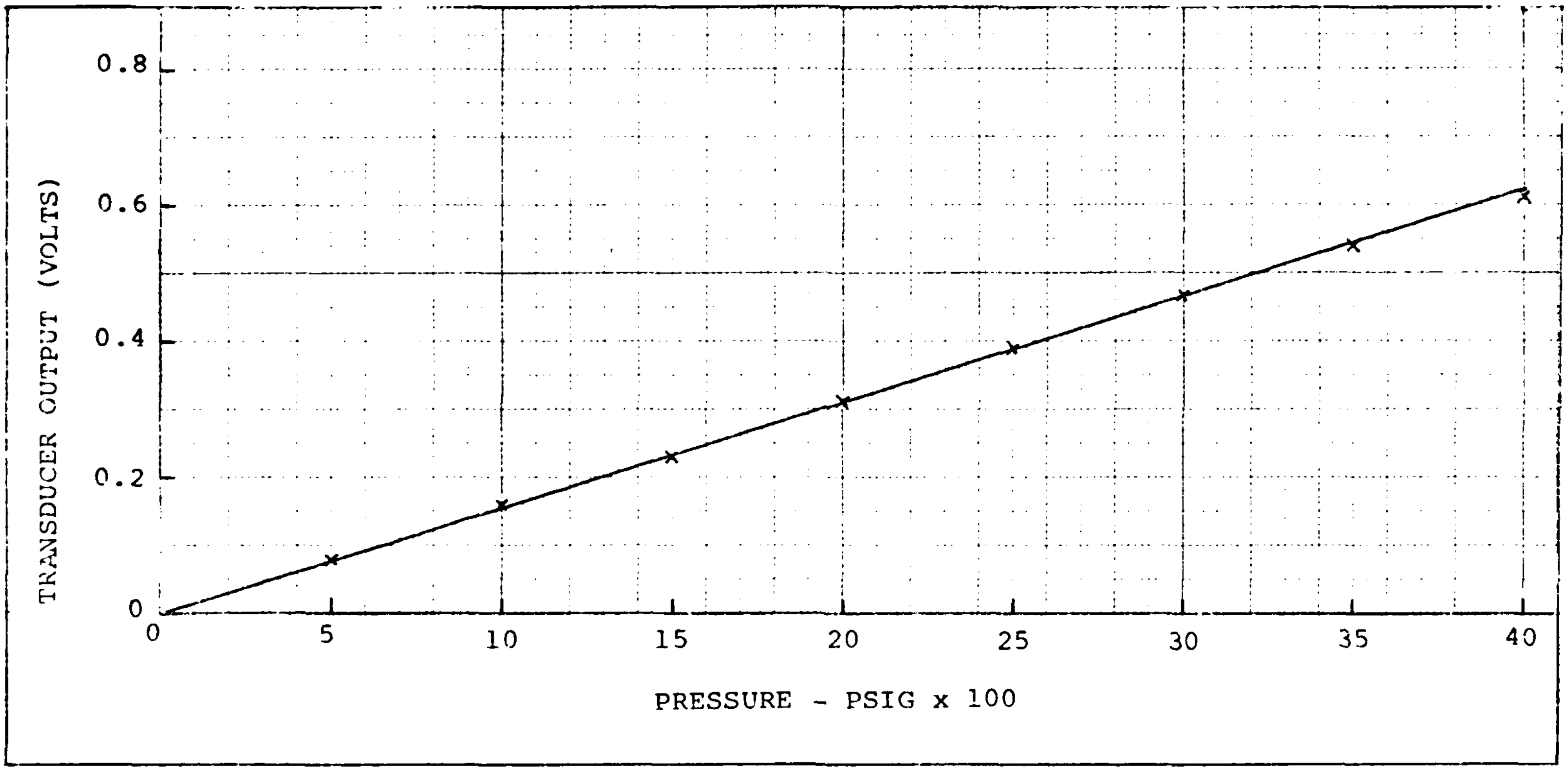

Figure. 2. Calibration Curve for Clamp on Transducer

obtained from pump speeds from 1500 rpm to 4500 rpm. Since the flow decreases with decreasing pump speed, a flow correction was needed to maintain constant flow rate. This was accomplished by changing the load valve down stream in the line.

Before turning off the pump, the clamp-on transducer was calibrated again.

Test Runs and Line Configurations

Several sets of runs were made in order to compare the measurements obtained with the in-line and clamp-on transducers and the transducer measurements and the computer predictions from HSFR.

The basic line configuration, shown in Fig 1, included two variations:

a. A hose connected between the pump and the line.

b. A tube instead of the hose. (The tube had the same dimensions as the main line).

With the hose, measurements were taken at the point 44 in. from the pump. With the tube, measurements were taken at two points (44 in. and 169 in. from the pump). Runs were made under two conditions: with a loose line, and with the line clamped on each side of the transducers.

Additional runs were made when the line was clamped every 10 to 20 in. Also, runs were made when the span between the clamps at the mid-point of the line was varied from 10 in. to 110 in. and the remainder of the line was

clamped every 10 to 20 in. In these tests, the in-line and clamp-on transducers were installed side by side at the middle of the span (169 in. position).

Several runs were made in order to compare the measurements of two clamp-on transducers mounted in the original clamps and to compare the measurements of two clamp-on transducers in which one of them was mounted in the original clamp while the second was mounted in the modified clamp.

IV. Results and Discussion

Many runs were made in order to compare between the in-line and clamp-on transducers.

The frequency range investigated was from 1500 rpm to 4500 rpm (225 Hz to 675 Hz). The fluid flow rate was 1 gpm. This flow rate was selected because the heat exchanger was not able to maintain a constant temperature at a higher flow. Even at that flow, the temperature varied slightly (10°F to 15°F) during the runs.

A set of runs was made with a hose that was connected between the pump and the line. The hose reduced the mechanical vibrations transmitted from the pump. The pressures were measured at a point 44 in. from the pump. These runs were made with two conditions: a clamped line, clamps on either side of the transducers and an unclamped (free) line. Figures 3 and 4, and Tables B-I and B-II, present the results of these runs. The maximum pressure peaks were around 150 psi. The correlation between the two transducers was much better with a clamped line than with the unclamped line. Figure 5 shows the correlation between the in-line transducer in the clamped configuration and the HSFR program curve. The correlation was very poor. The program failed to predict the frequency and the amplitude at resonant frequencies. The reason for that failure is that the model for the hose was not accurate enough. The predicted amplitudes were much lower than measured values except in

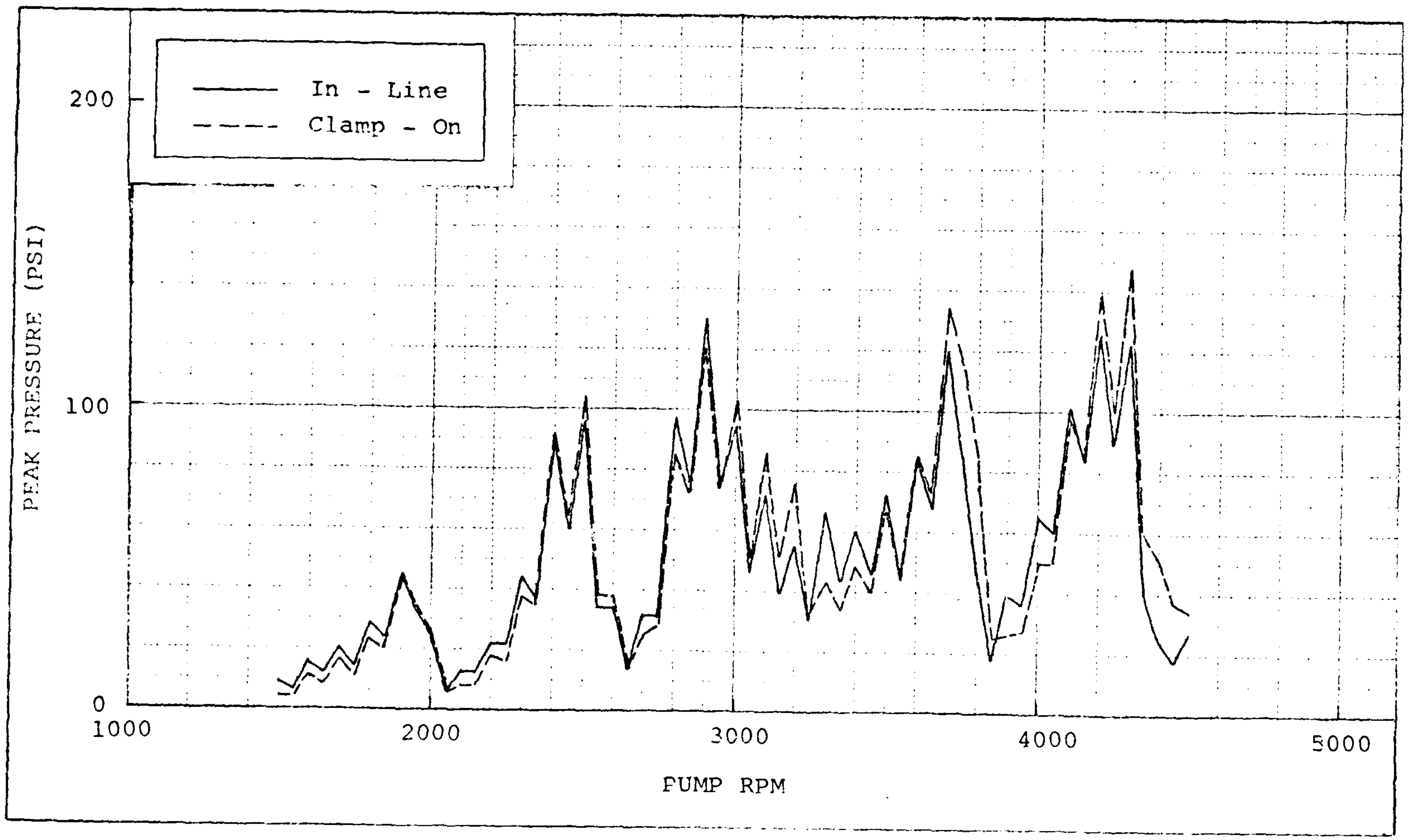

Figure. 3. In Line - Clamp on Correlation
44 in. from Pump. Clamped Line, with Hose

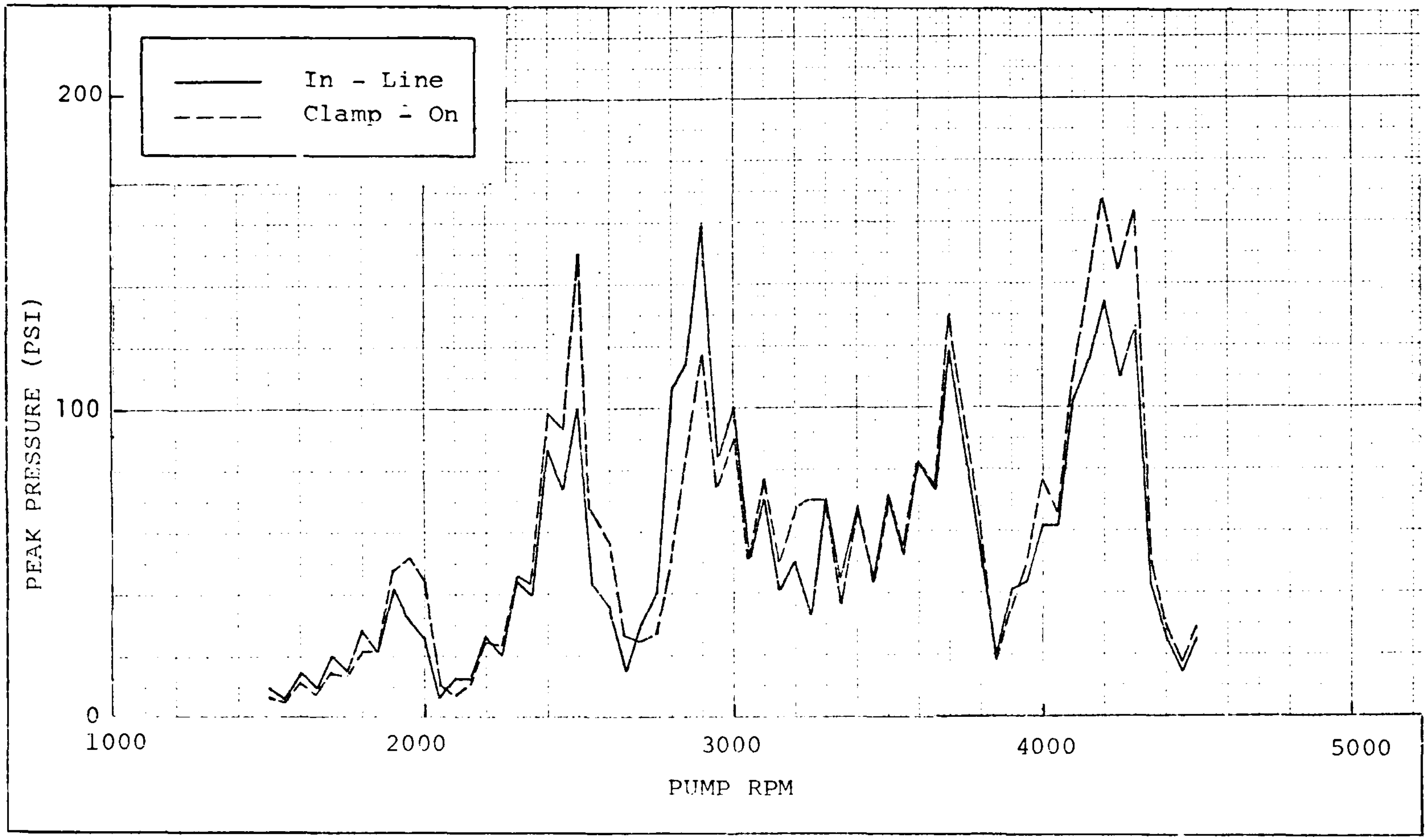

Figure. 4. In Line - Clamp on Correlation
44 in. from Pump. Unclamped Line, with Hose

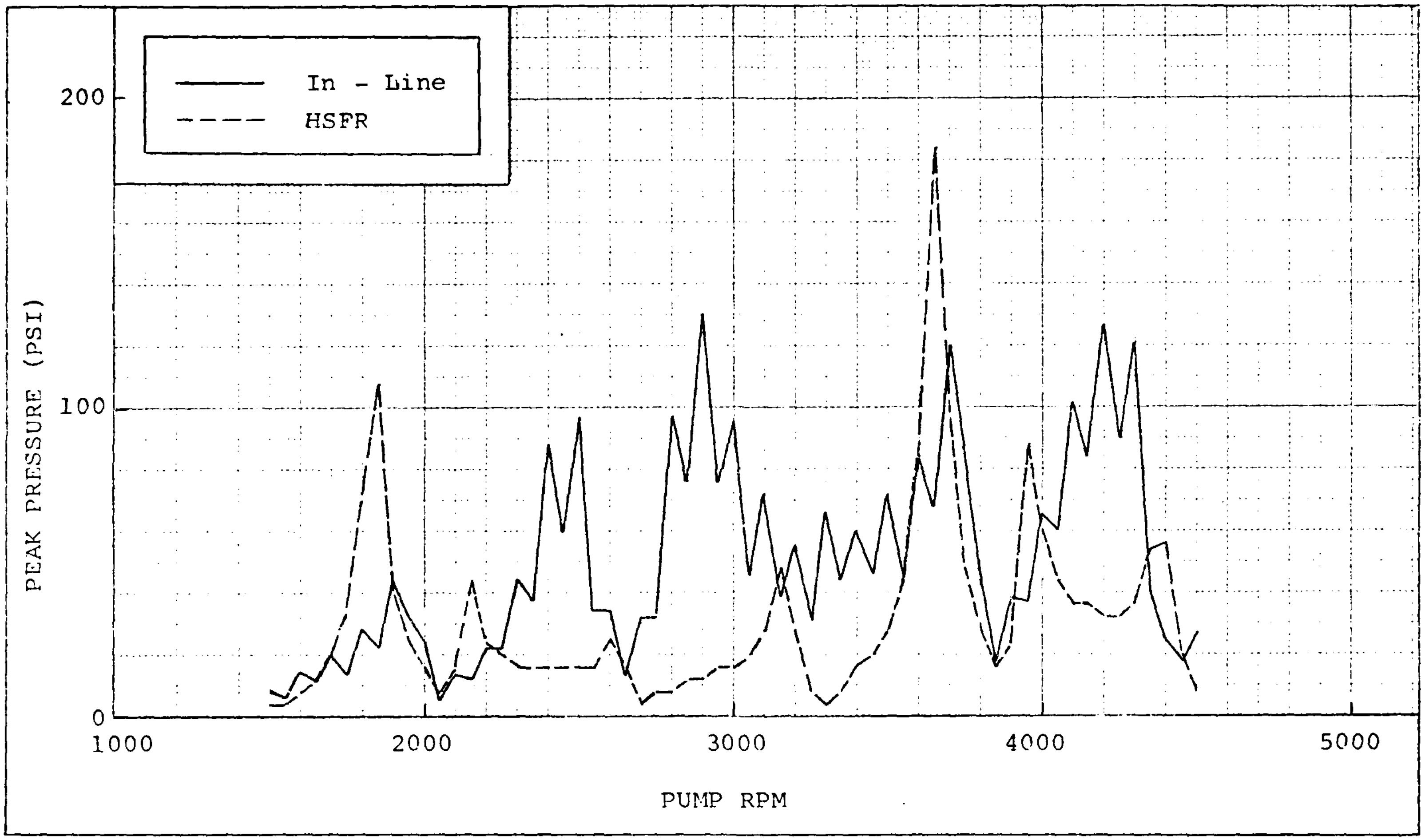

Figure. 5. In Line - HSFR Correlation
44 in. from Pump. Clamped Line, with Hose

two frequencies, 1800 rpm and 3600 rpm. These frequencies might be predicted resonant frequencies.

In the next set of runs, the hose was replaced by a tube with the same dimensions as the main line. The pressure was measured at two locations, 44 in. and 169 in. from the pump, again with a clamped line and unclamped line. Figures 6 to 8, and Tables B-III and B-IV present the results for the 44 in. location. Figures 9 to 11, and Tables B-V and B-VI present the results for the 169 in. The maximum pressure peaks (approximately 450 psi) were much higher than the pressure peaks with the hose configuration. At the 44 in. location, the correlation between the two transducers was very good with a clamped line (Fig 6), and not as good with an unclamped line (Fig 7). Both transducers agreed in resonant frequencies and in the amplitudes. At the 169 in. location, the correlation between the two transducers was good with a clamped configuration (Fig 9), and not as good with an unclamped line (Fig 10). Figures 8 and 11 show the correlation between the in-line transducer in the clamped configuration and the HSFR program curve at the two locations. The deviation in the resonant frequency locations ranged from 50 to 100 rpm at 4500 rpm or approximately 2%. Predicted amplitudes ranged from 0 to 30% lower than the actual measured amplitudes of the pressure pulsations. Previous studies (Ref 3:64) showed in some cases higher predicted values by HSFR than the actual measured pressure pulsations. A 2% correlation

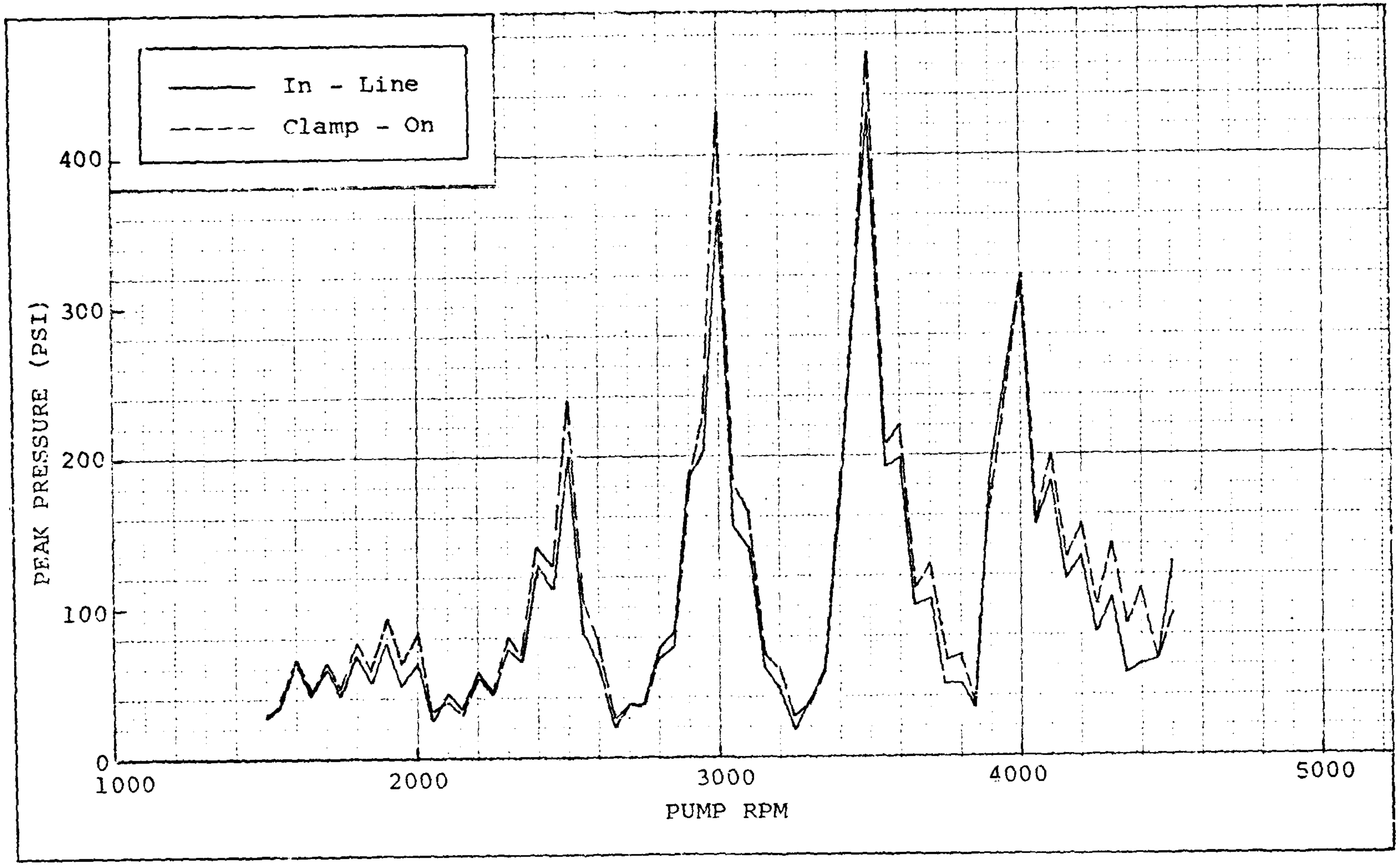

Figure. 6. In Line - Clamp on Correlation
44 in. from Pump. Clamped Line, with Tube.

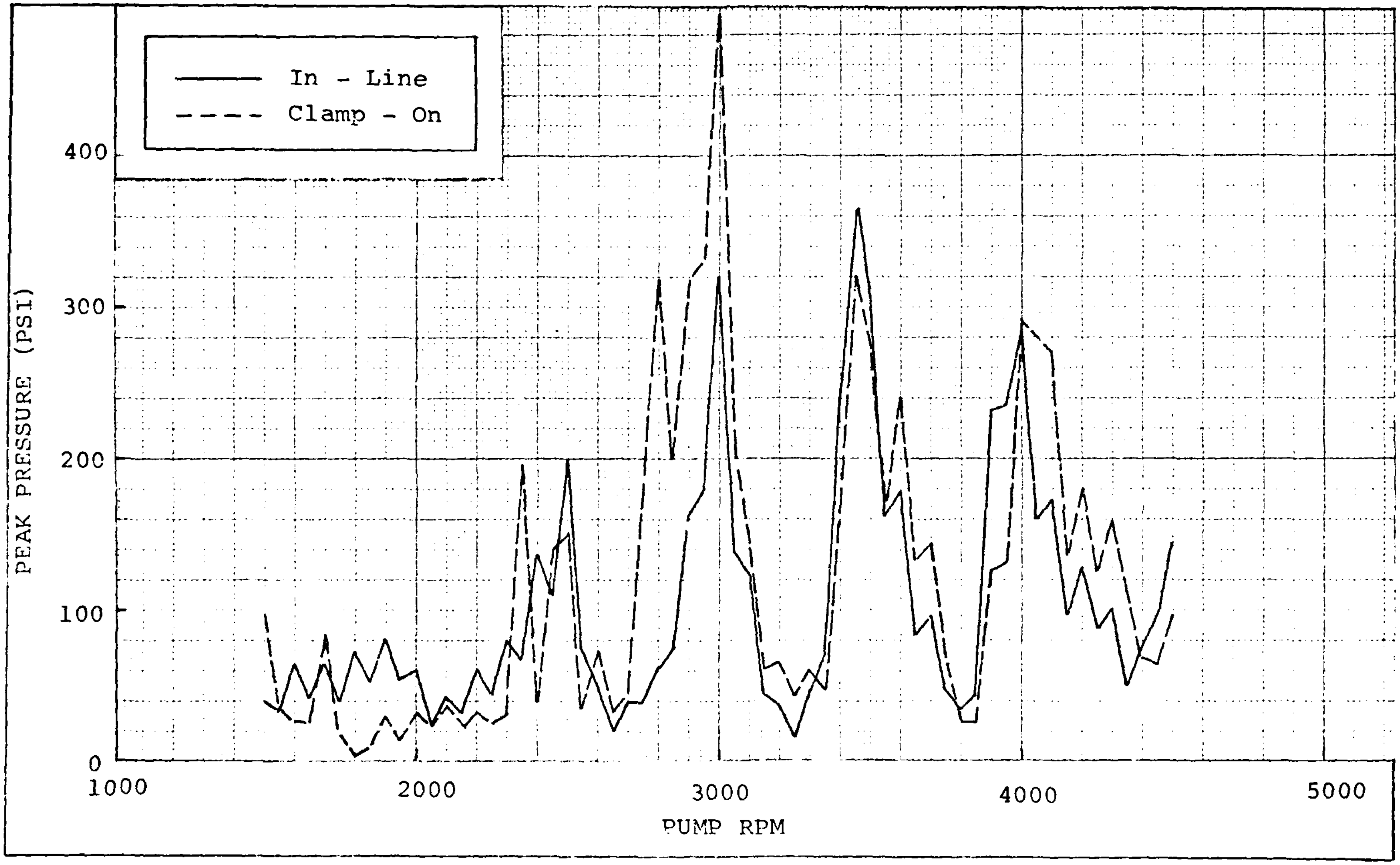

Figure. 7. In Line - Clamp on Correlation
44 in. from Pump. Unclamped Line, with Tube

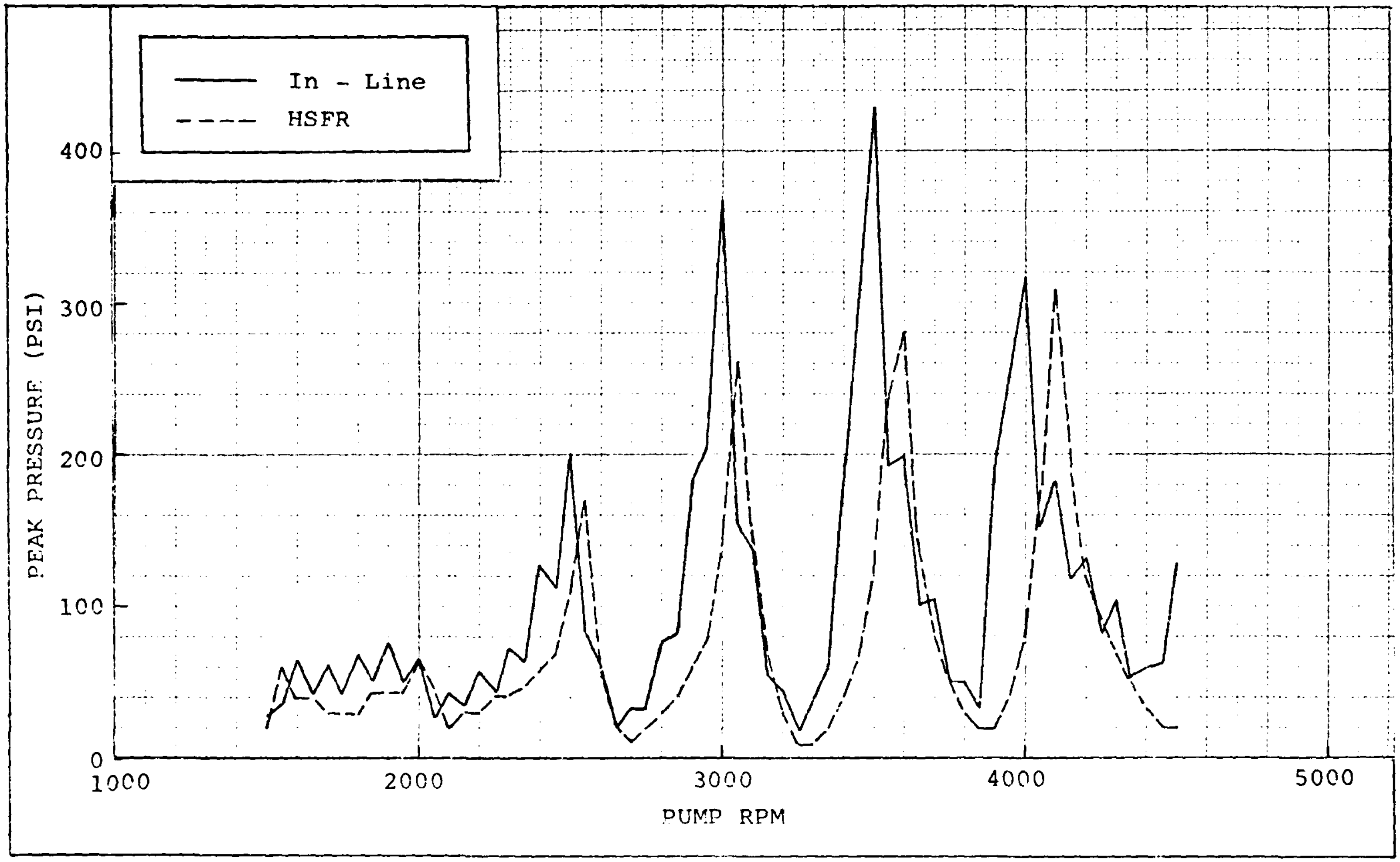

Figure. 8. In Line - HSFR Correlation
44 in. from Pump. Clamped Line, with Tube

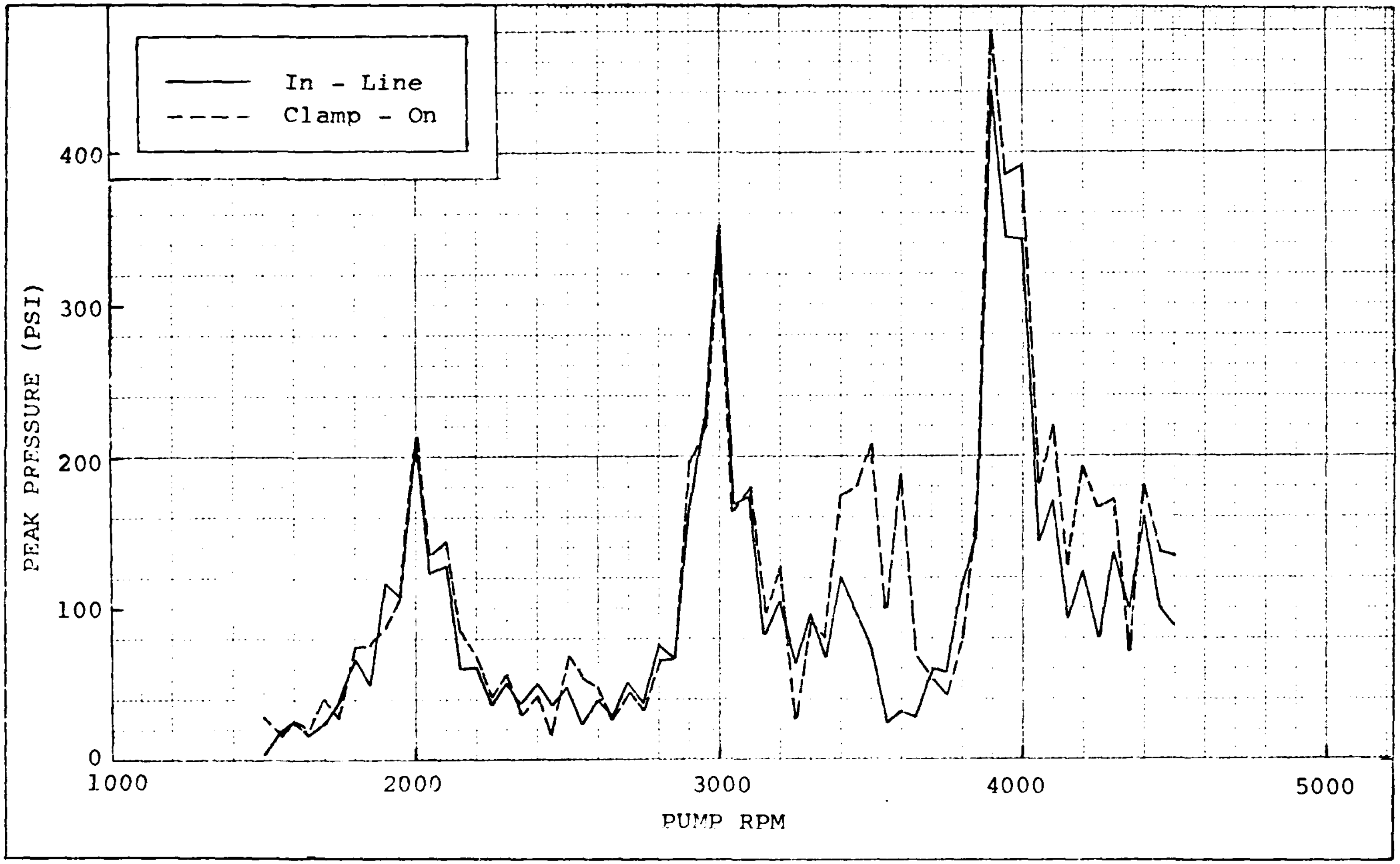

Figure. 9. In Line - Clamp on Correlation
169 in. from Pump. Clamped Line with Tube

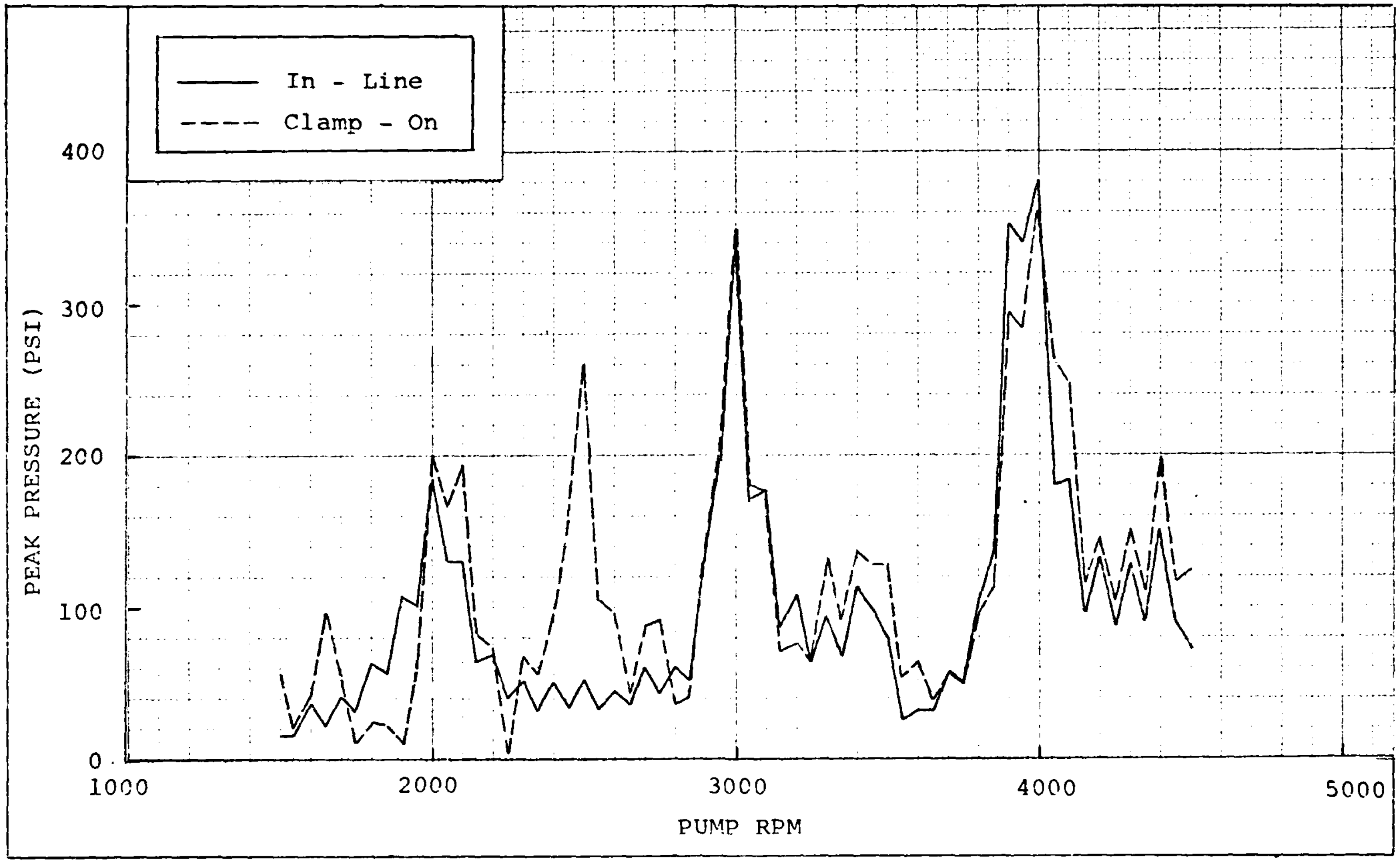

Figure. 10. In Line - Clamp on Correlation
169 in. from Pump. Unclamped Line with Tube

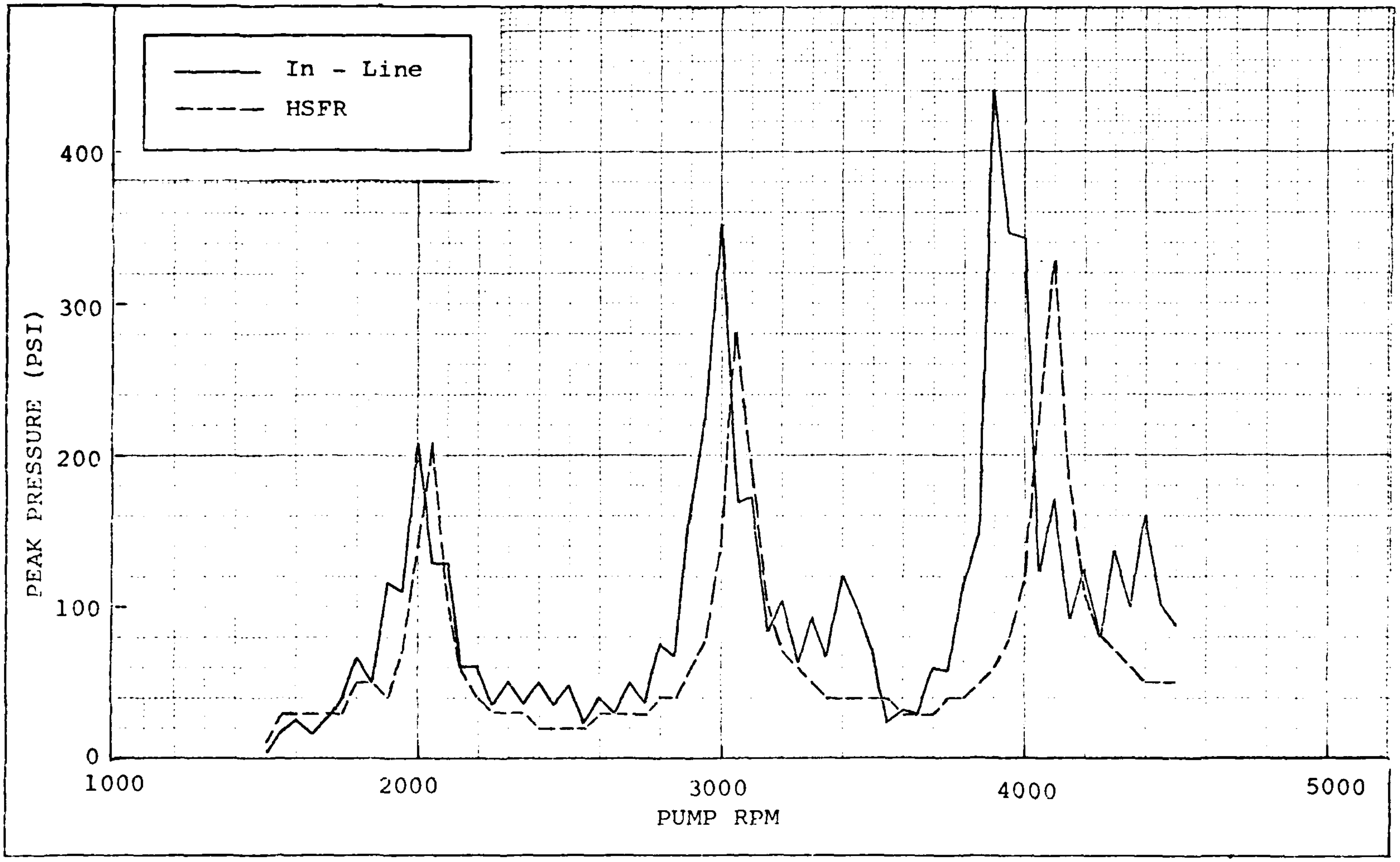

Figure. 11. In Line - HSFR Correlation
169 in. from Pump. Clamped Line, with Tube

in resonant frequencies is good considering possible errors due to temperature shift during the run, circuit length errors, and fluid property and instrumentation errors.

Appendix C contains the input data and the output plots from HSFR. Details on the hose bulk modulus measurements are given in Appendix A. As a result of these runs, it was clear from the experimental results that line longitudinal vibrations had a definite effect on the correlation between the two transducers. The disagreement was greater at 169 in. location because the unclamped length was greater.

Another set of runs was made in order to find correlation between the transducers as a function of the span between the clamps. Tables B-VII to B-XII present the results for these runs. Table I shows the differences between the in-line and clamp-on transducers based on average differences found in the various spans and ranges of frequency.

The basic assumption is that the in-line transducer is measuring the correct values for the oscillatory pressures. Fluid fluctuations are acting directly on the transducer sensing element. On the other hand the clamp on transducer is activated by the strain that occurs in the contact point between the transducer and the tube. This strain is not a pure strain due to the internal pressure. It is a combination of several strains as follows:

Table I

Differences (Percents) between In-Line
and Clamp-On Transducers
(Related to the In-Line Transducer)

Span	10 in.		30 in.	
Frequency (RPM) (Hz)	1500-3300 225-500	3300-4500 500-675	1500-3300 225-500	3300-4500 500-675
Pressure > 100 PSI	± 10 %	+ 20 %	± 10 %	+ 25 %
Pressure < 100 PSI	± 10 %	± 15 %	± 15 %	± 20 %

Span	50 in.		70 in.	
Frequency (RPM) (Hz)	1500-3300 225-500	3300-4500 500-675	1500-3300 225-500	3300-4500 500-675
Pressure > 100 PSI	± 10 %	+ 25 %	± 15 %	+ 20 %
Pressure < 100 PSI	± 20 %	± 25 %	± 15 %	± 15 %

Span	90 in.		110 in.	
Frequency (RPM) (Hz)	1500-3300 225-500	3300-4500 500-675	1500-3300 225-500	3300-4500 500-675
Pressure > 100 PSI	+ 15 %	+ 25 %	+ 15 %	+ 25 %
Pressure < 100 PSI	± 15 %	+ 20 %	± 15 %	+ 25 %

1) Strain due to internal pressure.

2) Strain due to changes in temperature.

3) Strain due to the vibrations in the line.

The internal pressure and temperature changes cause only tension stresses at the contact point. The stresses due to vibrations may be tension or compression. Poisson's theory states that for an axial elongation (including bending) of a bar or tube, a lateral contraction occurs and conversely, for any axial compression, a lateral expansion occurs. The ratio of the unit lateral contraction to the unit axial elongation is called Poisson's ratio and has a value of 0.305 for stainless steel tube. Furthermore, Bold (Ref 5) conducted experiments in order to determine the stresses developed in tubing while under pressure, or due to bending, or both. These experiments confirmed the theory that a tube, if bent up to the elastic limit, is longitudinally in tension on one side while at the same location it is circumferentially in compression, and conversely, a tube if bent down to the elastic limit is longitudinally in compression while at the same location it is circumferentially in tension. As the combined longitudinal stresses are generally higher, they are the controlling stresses which should be considered in tubing flexures. The combined stress is obtained by adding arithmetically: the longitudinal fluid pressure stress, the longitudinal thermal stress and the longitudinal bending stress. While the fluid pressure strain and the thermal strain are always

tension (+), and the bending strain may be tension or compression, (+) or (-), the combined strain may be greater than or less than the strain due to the internal fluid pressure. This would explain why the clamp-on transducer measured lower values than the in-line transducer (the combined strain is less than the strain due to internal pressure alone). As far as bending was concerned, the bending stresses or strains are affected by the transverse displacement. Housner (Ref 8) found the equation for the transverse displacement Z is:

$$EI\,\frac{\partial^4 Z}{\partial X^4} + \rho V^2\,\frac{\partial^2 Z}{\partial X^2} + 2\rho V\,\frac{\partial^2 Z}{\partial t\,\partial X} + M\,\frac{\partial^2 Z}{\partial t^2} = 0 \qquad (2)$$

Z - the vertical co-ordinate

X - the horizontal co-ordinate along the tube

ρ - fluid density per unit length of pipe

M - total mass, pipe plus fluid per unit length

V - velocity of fluid

E - modulus of elasticity of pipe

I - moment of inertia of pipe

This equation states that the line is acted upon by three different inertia forces:

$\rho V^2 \frac{\partial^2 Z}{\partial X^2}$ - Inertia force associated with the change in direction of V, enforced by the curvature of the line, that is the fluid experiences an acceleration because it travels along a

curved path.

$2\rho V \dfrac{\partial^2 Z}{\partial t \partial X}$ - Inertia force associated with the Coriolis acceleration which arises because the fluid is flowing with velocity V relative to the pipe, while the pipe itself has an angular velocity $\dfrac{\partial^2 Z}{\partial t \partial X}$ at any point along its length.

$M \dfrac{\partial^2 Z}{\partial t^2}$ - Inertia force associated with the vertical acceleration of the pipe.

Housner's equation shows that the displacement, or the bending stresses that are associated with the displacement, is affected by the dimensions and the properties of the line and by the boundary conditions. Based on the strong dependence on fluid and line properties, it is clear that the results given in Table I are exactly for the line that was used in these experiments.

The repeatability of the in-line transducer was much better than that of the clamp-on transducer. This confirms the assumption that the in-line transducer was not affected very much by the clamping conditions or the vibrations.

Several runs were made in order to compare the measurements of the two original designed clamp-on transducers. Tables B-XIII to B-XV present the results of these runs. The differences in readings between the two transducers that were mounted side by side ranged from 10 to 15%. Additional runs were made in order to compare the measurements

of the original clamp-on transducer with another transducer mounted in a modified clamp. The differences in reading were up to ± 25% thus the modified clamp did not improve the correlation between the clamp-on and the in-line transducers.

Figure 12 shows the standing wave patterns that are generated at the resonant frequencies. The pressures measured at the resonant frequencies are a function of transducer location. As shown in Fig 12, the in-line transducer at 169 in. location was installed at the waves peak. The clamp-on transducer was mounted side by side with the in-line transducer, which means that the measurements were not affected very much by their locations.

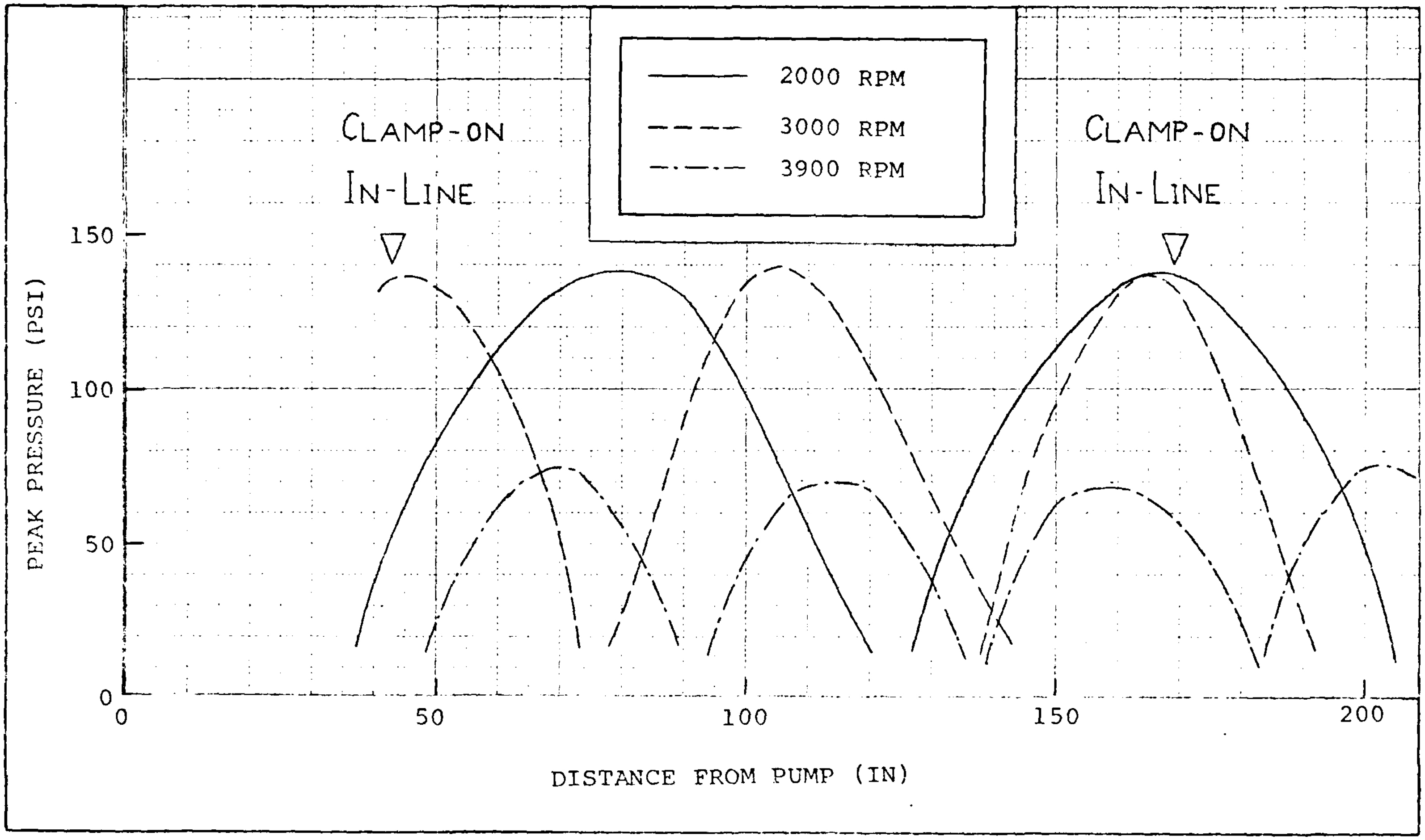

Figure. 12. Standing Wave Patterns

V. Conclusions

The in-line pressure transducer is more accurate for measuring the in-line fluid pressure pulsations than the clamp-on transducer, because the clamp-on transducer is measuring a combination of strains and not only the strain due to internal pressure. The clamp-on pressure transducer measurements are affected by the mechanical vibrations in the line. The deviation between the two transducers ranged up to ± 25 % depending on the clamping conditions. The deviation increased with higher pressure amplitude signals and the increasing of the distance between the clamps.

It is advantageous to use a clamp-on roving piezoelectric transducer for easy mounting along the line for mapping of standing pressure waves. If high accuracy is needed, in-line pressure transducers should be installed at the pressure peak locations in order to measure the oscillatory pressure.

In many engineering situations, the resonant frequency locations are of prime importance. In such cases, both clamp-on and in-line transducers provide accurate results which agree well with predicted results by HSFR.

The hose in the system causes a significant reduction in the oscillatory pressure amplitudes, but the hose model results did not compare well with the test data. The computer predicted results were much lower than measured values. Not all of the resonant frequencies were predicted by HSFR

with the hose. All the resonant frequencies were predicted well with the ~~tube~~ installed in the system.

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APPENDIX A

Hose Bulk Modulus Measurement

Appendix A

Hose Bulk Modulus Measurement

For good system simulations, the HSFR computer program for the system requires an accurate value of the bulk modulus for the hose. Figure A-1 describes the hose bulk modulus measurement setup. The setup was designed to measure the change in hose volume due to pressure. This was determined by measuring the amount of oil the hose would hold under each pressurized and unpressurized condition. The amount of oil in each case was determined by allowing the oil to empty into a buret. The change in hose volume was determined for different pressure. The results are tabulated in Table A-1 and shown also in Figure A-2.

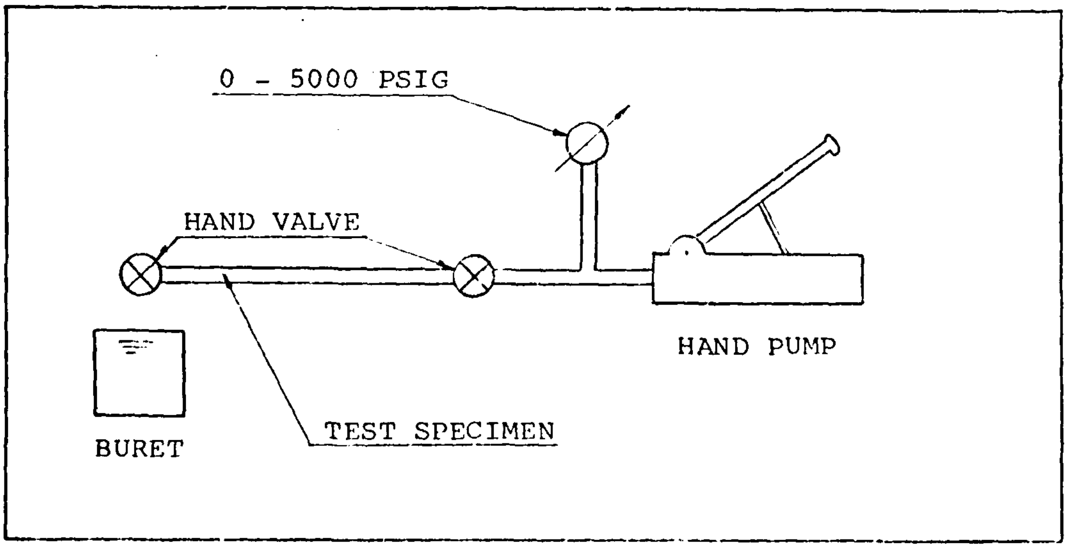

Figure. A-1. Hose Bulk Modulus Measurements Setup

Table A-I

MEASURED VOLUME CHANGE (ΔV) FOR THE HOSE

Pressure (PSI)	Change In Volume (ml)	$Bulk_e$ (PSI)
3000	20	150
2500	16.5	152
2000	12	167
1000	7	143

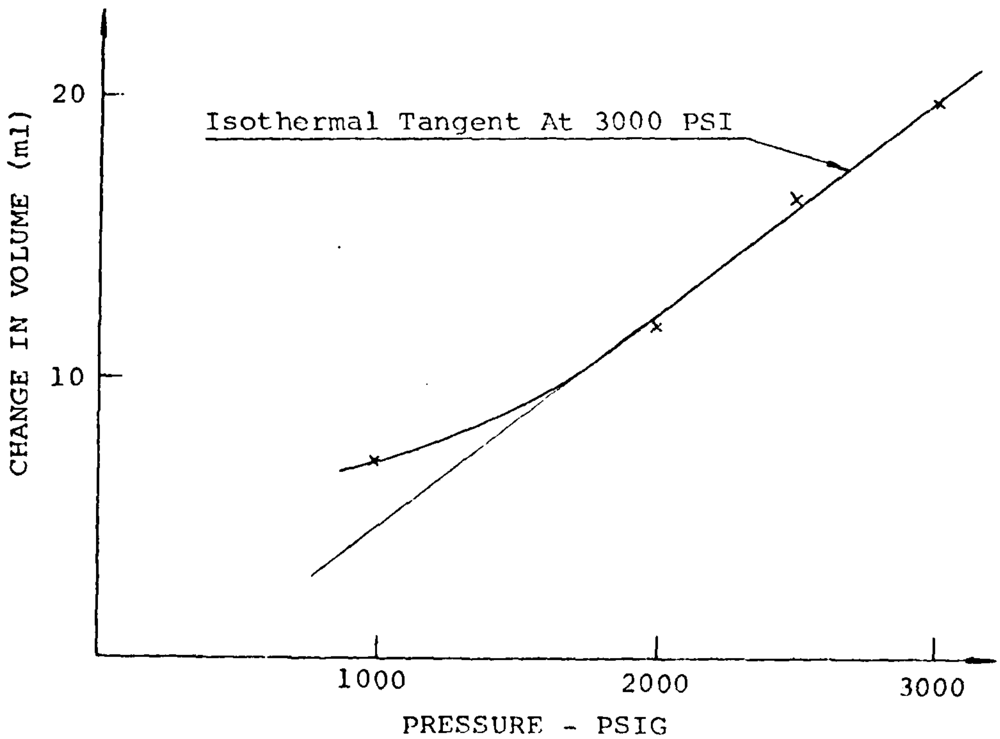

Figure. A-2. Change in Volume Vs. Pressure

The hose volume under no pressure was 350 ml. The bulk modulus was determined from the following equation:

$$Bulk_e = \frac{\Delta P}{\Delta V / V} \qquad (3)$$

Where: ΔP = Change in pressure

ΔV = Change in volume due to pressure

V = Volume of hose

$Bulk_e$ = Equivalent bulk modulus of the hose and the oil.

The effective bulk modulus is obtained from the following equation:

$$\frac{1}{Bulk_e} = \frac{1}{Bulk_{hose}} + \frac{1}{Bulk_{oil}} \qquad (4)$$

Thus the bulk modulus of the hose is:

$$Bulk_{hose} = \frac{Bulk_e \cdot Bulk_{oil}}{Bulk_{oil} - Bulk_e} \qquad (5)$$

The value for the isothermal tangent bulk modulus of oil (MIL-H-5606B) at temperature of 75°F and pressure of 3000 PSI is 223,551 PSI (Ref 3:338).

From Equation (3)

$$Bulk_e = \frac{3000}{20/350} = 52,500 \text{ PSI}$$

Substituting into Equation (5)

$$Bulk_{hose} = \frac{52500 \cdot 223551}{223551 - 52500} = 68613 \text{ PSI}$$

APPENDIX B

Experimental Data

Appendix B

Experimental Data

This appendix contains the experimental data that was obtained during the investigation. The pressure data is presented in tables as a function of frequency. Typical results are presented for certain cases. In some cases the results presented are an average of several runs at the same conditions.

The following remarks are given to clarify the table headings:

1. HSFR - Hydraulic System Frequency Response. This is a digital computer program that was developed by McDonnell Aircraft Company. It predicts how oscillatory flows and pressures caused by the acoustical energy content of a pump outlet are transmitted through the lines and components of hydraulic system.
2. Clamped Line - The line was tightened only close to the transducers in order to eliminate free vibrations.
3. Unclamped Line - The line was rested on the floor, free to vibrate.
4. Hose - The runs were made when a hose was connected between the pump outlet and the line.
5. Tube - The runs were made when a tube with the same

dimensions as the whole line was connected between the pump outlet and the line.

6.

$$\Delta P(\%) = \frac{P_{in\ line} - P_{clamp\ on}}{P_{in\ line}} \times 100 \qquad (6)$$

7. Span - The distance between two clamps. The transducers were located in the center of the span.

8. The frequency introduced from 4500 RPM to 1500 RPM in the same order that it was measured due to temperature problem.

Table B-I

In Line - Clamp On - HSFR Correlation
44 in. from pump
Clamped Line With Hose

Pump Speed (RPM)	Pressure (PSI)			Pump Speed (RPM)	Pressure (PSI)		
	In-Line	Clamp-On	HSFR		In-Line	Clamp-On	HSFR
4500	27	33	8	3700	119	134	96
4450	18	37	20	3650	68	73	184
4400	25	51	56	3600	83	85	84
4350	40	60	44	3550	45	45	44
4300	121	147	36	3500	72	66	21
4250	89	99	32	3450	46	40	20
4200	126	139	32	3400	60	47	16
4150	84	85	36	3350	44	37	8
4100	101	97	36	3300	66	43	4
4050	60	50	44	3250	31	32	8
4000	65	50	60	3200	55	76	21
3950	37	27	88	3150	39	52	48
3900	39	26	24	3100	72	87	28
3850	18	25	16	3050	46	51	20
3800	46	84	28	3000	95	103	16
3750	85	113	48	2950	76	74	16

Table B-I
(cont.)

Pump Speed (RPM)	Pressure (PSI)			Pump Speed (RPM)	Pressure (PSI)		
	In-Line	Clamp-On	HSFR		In-Line	Clamp-On	HSFR
2900	129	120	12	2100	14	8	16
2850	76	71	12	2050	6	5	8
2800	97	83	8	2000	24	26	16
2750	32	28	8	1950	32	34	24
2700	34	25	4	1900	44	43	40
2650	14	14	16	1850	24	20	108
2600	34	38	24	1800	28	22	72
2550	34	39	16	1750	14	11	32
2500	96	105	16	1700	20	16	20
2450	60	64	16	1650	12	9	12
2400	88	91	16	1600	15	11	8
2350	37	35	16	1550	7	4	4
2300	44	37	16	1500	9	4	4
2250	22	16	20				
2200	22	18	24				
2150	12	8	44				

Table B-II

In Line - Clamp On - HSFR Correlation
44 in. from pump
Unclamped Line With Hose

Pump Speed (RPM)	Pressure (PSI)			Pump Speed (RPM)	Pressure (PSI)		
	In-Line	Clamp-On	HSFR		In-Line	Clamp-On	HSFR
4500	25	29	8	3700	118	130	96
4450	15	17	20	3650	74	74	184
4400	25	40	56	3600	82	82	84
4350	43	59	44	3550	52	52	44
4300	126	164	36	3500	71	72	28
4250	111	147	32	3450	46	45	20
4200	134	168	32	3400	67	63	16
4150	115	141	36	3350	44	37	8
4100	102	108	36	3300	69	73	4
4050	62	64	44	3250	33	73	8
4000	61	76	60	3200	50	69	28
3950	44	51	88	3150	41	50	48
3900	41	35	24	3100	70	79	28
3850	20	18	16	3050	52	50	20
3800	53	64	28	3000	99	89	16
3750	81	94	28	2950	85	75	16

Table B-II
(cont.)

Pump Speed (RPM)	Pressure (PSI)			Pump Speed (RPM)	Pressure (PSI)		
	In-Line	Clamp-On	HSFR		In-Line	Clamp-On	HSFR
2900	158	137	12	2100	14	7	16
2850	114	86	12	2050	7	10	8
2800	106	49	8	2000	25	45	16
2750	40	27	8	1950	32	52	24
2700	29	25	4	1900	41	48	40
2650	18	27	16	1850	21	23	108
2600	35	57	24	1800	27	23	72
2550	42	67	16	1750	15	13	32
2500	90	150	16	1700	20	15	20
2450	74	91	16	1650	11	9	12
2400	87	98	16	1600	14	11	8
2350	40	43	16	1550	8	5	4
2300	44	45	16	1500	9	6	4
2250	21	23	20				
2200	26	24	24				
2150	13	11	44				

Table B-III

In Line - Clamp On - HSFR Correlation
44 in. from pump
Clamped Line With Hose

Pump Speed (RPM)	Pressure (PSI)			Pump Speed (RPM)	Pressure (PSI)		
	In-Line	Clamp-On	HSFR		In-Line	Clamp-On	HSFR
4500	128	93	20	3700	104	127	80
4450	64	61	20	3650	99	111	139
4400	59	110	41	3600	198	220	278
4350	54	88	49	3550	192	205	239
4300	104	140	69	3500	427	468	119
4250	82	102	89	3450	307	318	68
4200	132	154	119	3400	175	170	91
4150	118	132	189	3350	58	57	29
4100	182	199	308	3300	38	35	11
4050	154	157	179	3250	18	29	11
4000	315	313	80	3200	44	58	29
3950	250	242	41	3150	54	67	68
3900	195	165	20	3100	137	164	149
3850	32	37	20	3050	153	183	259
3800	49	69	29	3000	366	426	139
3750	50	65	49	2950	205	226	80

Table B-III
(cont.)

Pump Speed (RPM)	Pressure (PSI)			Pump Speed (RPM)	Pressure (PSI)		
	In-Line	Clamp-On	HSFR		In-Line	Clamp-On	HSFR
2900	184	185	59	2100	42	34	20
2850	82	74	41	2050	26	34	41
2800	75	65	29	2000	64	83	60
2750	33	27	20	1950	50	63	41
2700	32	25	11	1900	77	93	41
2650	20	24	20	1850	49	58	41
2600	59	78	60	1800	69	77	29
2550	82	105	169	1750	41	46	29
2500	198	238	109	1700	59	63	29
2450	112	129	69	1650	41	43	41
2400	127	140	60	1600	64	66	41
2350	63	69	49	1550	36	35	60
2300	71	81	41	1500	28	27	20
2250	43	45	41				
2200	55	52	29				
2150	33	28	29				

Table B-IV

In Line - Clamp On - HSFR Correlation
44 in. from pump
Unclamped Line With Tube

Pump Speed (RPM)	Pressure (PSI)			Pump Speed (RPM)	Pressure (PSI)		
	In-Line	Clamp-On	HSFR		In-Line	Clamp-On	HSFR
4500	146	97	20	3700	95	144	80
4450	101	65	20	3650	84	114	139
4400	75	68	41	3600	177	241	278
4350	49	109	49	3550	163	174	239
4300	102	158	69	3500	304	268	119
4250	88	126	89	3450	387	321	68
4200	129	180	119	3400	238	174	41
4150	95	137	189	3350	71	47	29
4100	173	270	308	3300	47	61	11
4050	160	278	179	3250	16	44	11
4000	283	290	80	3200	36	65	29
3950	236	131	41	3150	44	61	68
3900	231	126	20	3100	122	140	149
3850	43	25	20	3050	138	193	259
3800	37	26	29	3000	321	525	139
3750	47	64	49	2950	182	334	80

Table B-IV
(cont.)

Pump Speed (RPM)	Pressure (PSI)			Pump Speed (RPM)	Pressure (PSI)		
	In-Line	Clamp-On	HSFR		In-Line	Clamp-On	HSFR
2900	164	318	59	2100	42	35	20
2850	78	202	41	2050	23	24	41
2800	65	319	29	2000	60	33	60
2750	40	203	20	1950	54	13	41
2700	38	44	11	1900	79	30	41
2650	19	31	20	1850	52	11	41
2600	47	73	60	1800	71	4	29
2550	74	35	169	1750	40	16	29
2500	202	152	109	1700	64	86	29
2450	109	139	69	1650	42	26	41
2400	135	39	60	1600	65	27	41
2350	68	195	49	1550	34	36	60
2300	81	32	41	1500	39	96	20
2250	45	26	41				
2200	59	31	29				
2150	33	22	29				

Table B-V

In Line - Clamp On - HSFR Correlation
169 in. from pump
Clamped Line With Tube

Pump Speed (RPM)	Pressure (PSI)			Pump Speed (RPM)	Pressure (PSI)		
	In-Line	Clamp-On	HSFR		In-Line	Clamp-On	HSFR
4500	87	135	49	3700	59	53	29
4450	99	138	49	3650	29	67	29
4400	160	181	49	3600	32	187	29
4350	99	72	59	3550	25	100	41
4300	137	171	69	3500	70	201	41
4250	81	166	80	3450	97	180	41
4200	124	193	109	3400	120	174	41
4150	93	128	179	3350	67	80	41
4100	170	221	329	3300	94	89	49
4050	144	184	219	3250	65	26	59
4000	342	393	119	3200	105	128	69
3950	344	387	80	3150	85	96	100
3900	441	500	59	3100	171	181	188
3850	146	167	49	3050	168	165	278
3800	116	81	41	3000	352	340	139
3750	58	42	41	2950	223	215	80

Table B-V
(cont.)

Pump Speed (RPM)	Pressure (PSI)			Pump Speed (RPM)	Pressure (PSI)		
	In-Line	Clamp-On	HSFR		In-Line	Clamp-On	HSFR
2900	167	195	59	2100	127	145	100
2850	68	68	41	2050	124	136	209
2800	75	66	41	2000	208	214	139
2750	38	32	29	1950	108	103	69
2700	50	45	29	1900	116	87	41
2650	30	26	29	1850	50	76	49
2600	40	48	29	1800	66	74	49
2550	24	54	20	1750	39	28	29
2500	47	69	20	1700	25	40	29
2450	35	15	20	1650	17	20	29
2400	50	42	20	1600	26	27	29
2350	37	30	29	1550	15	15	29
2300	51	57	29	1500	5	30	11
2250	35	43	29				
2200	62	67	41				
2150	60	83	59				

Table B-VI

In Line - Clamp On - HSFR Correlation
169 in. from pump
Unclamped Line With Tube

Pump Speed (RPM)	Pressure (PSI)			Pump Speed (RPM)	Pressure (PSI)		
	In-Line	Clamp-On	HSFR		In-Line	Clamp-On	HSFR
4500	71	125	49	3700	55	55	29
4450	91	117	49	3650	32	40	29
4400	150	198	49	3600	33	63	29
4350	93	110	59	3550	26	54	41
4300	128	152	69	3500	78	127	41
4250	87	105	80	3450	98	126	41
4200	132	146	100	3400	114	137	41
4150	97	116	179	3350	69	92	41
4100	184	249	329	3300	94	131	49
4050	181	261	219	3250	65	67	59
4000	378	361	119	3200	109	76	69
3950	341	283	80	3150	87	71	100
3900	352	293	59	3100	177	173	188
3850	135	111	49	3050	171	180	278
3800	106	96	41	3000	339	348	139
3750	50	49	41	2950	195	207	80

Table B-VI
(cont.)

Pump Speed (RPM)	Pressure (PSI)			Pump Speed (RPM)	Pressure (PSI)		
	In-Line	Clamp-On	HSFR		In-Line	Clamp-On	HSFR
2900	139	137	59	2100	130	194	100
2850	54	41	41	2050	130	169	209
2800	61	36	41	2000	185	199	139
2750	45	93	29	1950	101	61	69
2700	59	88	29	1900	108	10	41
2650	35	33	29	1850	54	22	49
2600	46	95	29	1800	63	25	49
2550	31	104	20	1750	32	11	29
2500	52	258	20	1700	42	57	29
2450	34	159	20	1650	26	97	29
2400	50	99	20	1600	36	44	29
2350	32	57	29	1550	17	20	29
2300	52	69	29	1500	16	58	11
2250	40	5	29				
2200	68	75	41				
2150	63	82	59				

Table B-VII

In Line - Clamp On Transducer Correlation
Span = 10 in.

Pump Speed (RPM)	Pressure (PSI)		ΔP (%)	Pump Speed (RPM)	Pressure (PSI)		ΔP (%)
	In-Line	Clamp-On			In-Line	Clamp-On	
4500	53	78	47	2900	203	200	1
4400	152	205	35	2800	83	76	8
4300	141	160	13	2700	52	49	6
4200	129	140	9	2600	42	42	0
4100	159	165	4	2500	48	57	19
4000	295	280	5	2400	52	52	0
3900	471	417	11	2300	52	52	0
3800	133	112	16	2200	62	66	6
3700	61	68	21	2100	116	121	4
3600	36	34	6	2000	198	207	5
3500	62	105	69	1900	116	115	1
3400	123	162	32	1800	61	59	3
3300	96	132	37	1700	38	34	10
3200	103	96	7	1600	35	30	14
3100	162	150	7	1500	19	17	11
3000	343	330	4				

Table B-VIII

In Line - Clamp On Transducer Correlation
Span = 30 in.

Pump Speed (RPM)	Pressure (PSI)		ΔP	Pump Speed (RPM)	Pressure (PSI)		ΔP
	In-Line	Clamp-On	(%)		In-Line	Clamp-On	(%)
4500	52	64	23	2900	205	199	2
4400	155	137	12	2800	82	77	6
4300	142	187	32	2700	52	45	13
4200	130	136	5	2600	42	34	19
4100	159	196	23	2500	47	54	15
4000	295	340	15	2400	51	59	15
3900	468	630	35	2300	51	55	8
3800	130	140	8	2200	61	64	5
3700	62	60	3	2100	116	127	9
3600	36	31	14	2000	198	200	1
3500	60	73	22	1900	116	114	2
3400	122	163	34	1800	63	60	5
3300	96	100	4	1700	41	34	17
3200	103	104	1	1600	34	30	12
3100	160	158	1	1500	19	18	5
3000	338	319	6				

Table B-IX

In Line - Clamp On Transducer Correlation
Span = 50 in.

Pump Speed (RPM)	Pressure (PSI)		ΔP	Pump Speed (RPM)	Pressure (PSI)		ΔP
	In-Line	Clamp-On	(%)		In-Line	Clamp-On	(%)
4500	57	80	40	2900	189	171	10
4400	151	184	22	2800	82	73	11
4300	139	179	29	2700	51	41	19
4200	131	164	25	2600	42	32	24
4100	163	200	23	2500	50	59	18
4000	312	375	20	2400	52	57	10
3900	430	640	49	2300	53	55	4
3800	129	102	21	2200	64	63	2
3700	61	48	21	2100	125	126	1
3600	36	24	34	2000	191	203	6
3500	71	105	48	1900	111	105	5
3400	115	136	18	1800	61	58	5
3300	96	104	8	1700	40	33	18
3200	105	109	4	1600	35	27	23
3100	168	173	3	1500	17	20	18
3000	353	352	0.5				

Table B-X

In Line - Clamp On Transducer Correlation
Span = 70 in.

Pump Speed (RPM)	Pressure (PSI)		ΔP	Pump Speed (RPM)	Pressure (PSI)		ΔP
	In-Line	Clamp-On	(%)		In-Line	Clamp-On	(%)
4500	47	109	132	2900	206	217	5
4400	141	182	29	2800	84	76	10
4300	135	153	13	2700	52	47	10
4200	128	120	6	2600	43	43	0
4100	157	167	6	2500	49	60	22
4000	290	279	4	2400	51	60	17
3900	477	543	14	2300	52	59	13
3800	130	142	10	2200	62	81	27
3700	64	73	14	2100	115	139	21
3600	37	36	3	2000	194	177	9
3500	60	77	28	1900	115	108	6
3400	118	146	29	1800	62	57	8
3300	96	110	15	1700	40	33	18
3200	103	122	18	1600	35	31	14
3100	162	179	10	1500	19	17	12
3000	343	364	6				

Table B-XI

In Line - Clamp On Transducer Correlation
Span = 90 in.

Pump Speed (RPM)	Pressure (PSI)		ΔP	Pump Speed (RPM)	Pressure (PSI)		ΔP
	In-Line	Clamp-On	(%)		In-Line	Clamp-On	(%)
4500	75	87	16	2900	185	188	2
4400	134	168	25	2800	79	78	1
4300	136	178	31	2700	51	47	8
4200	132	179	36	2600	43	48	12
4100	173	202	17	2500	51	51	0
4000	339	384	13	2400	52	63	21
3900	391	504	26	2300	53	73	38
3800	124	141	15	2200	67	60	4
3700	60	83	38	2100	131	149	14
3600	36	36	0	2000	193	218	13
3500	78	101	29	1900	109	115	6
3400	112	122	9	1800	53	59	11
3300	96	114	19	1700	40	33	18
3200	108	125	16	1600	35	30	13
3100	180	195	8	1500	18	17	6
3000	360	369	3				

Table B-XII

In Line - Clamp On Transducer Correlation
Span = 110 in.

Pump Speed (RPM)	Pressure (PSI)		ΔP	Pump Speed (RPM)	Pressure (PSI)		ΔP
	In-Line	Clamp-On	(%)		In-Line	Clamp-On	(%)
4500	81	135	67	2900	171	181	6
4400	146	188	29	2800	75	67	11
4300	134	171	28	2700	51	45	12
4200	134	157	17	2600	43	66	55
4100	179	193	8	2500	53	52	2
4000	362	424	17	2400	52	56	8
3900	366	327	11	2300	54	58	8
3800	111	160	44	2200	67	78	16
3700	59	69	17	2100	134	159	19
3600	37	73	97	2000	130	207	9
3500	84	127	51	1900	107	109	2
3400	110	141	28	1800	59	56	5
3300	97	119	23	1700	39	34	13
3200	111	131	19	1600	35	37	6
3100	189	211	12	1500	16	18	13
3000	372	407	9				

Table B-XIII

Two Clamp On Transducers Correlation
Span = 10 in.

Pump Speed (RPM)	Pressure (PSI)			Pump Speed (RPM)	Pressure (PSI)		
	In-Line	Clamp-On A	Clamp-On B		In-Line	Clamp-On A	Clamp-On B
4500	86	134	148	2900	161	178	159
4400	147	196	200	2800	76	78	67
4300	134	160	159	2700	51	51	41
4200	135	149	145	2600	44	40	31
4100	184	197	188	2500	53	56	71
4000	376	385	359	2400	53	63	64
3900	313	279	265	2300	55	62	60
3800	107	68	69	2200	66	75	72
3700	54	29	27	2100	133	146	139
3600	34	45	43	2000	192	208	196
3500	95	213	198	1900	107	110	104
3400	117	179	166	1800	61	61	54
3300	97	165	137	1700	40	35	32
3200	113	152	132	1600	35	31	27
3100	192	218	205	1500	17	13	12
3000	375	418	383				

Table B-XIV

Two Clamp On Transducers Correlation
Span = 30 in.

Pump Speed (RPM)	Pressure (PSI) In-Line	Pressure (PSI) Clamp-On A	Pressure (PSI) Clamp-On B	Pump Speed (RPM)	Pressure (PSI) In-Line	Pressure (PSI) Clamp-On A	Pressure (PSI) Clamp-On B
4500	98	173	173	2900	143	145	136
4400	146	216	207	2800	73	72	65
4300	134	177	165	2700	50	47	40
4200	139	163	155	2600	44	40	34
4100	197	251	229	2500	56	67	75
4000	413	489	444	2400	53	58	60
3900	267	329	281	2300	56	60	60
3800	98	114	95	2200	73	78	78
3700	52	58	42	2100	144	156	153
3600	35	35	34	2000	188	198	194
3500	110	128	155	1900	98	100	95
3400	114	127	132	1800	59	58	53
3300	97	101	104	1700	40	35	31
3200	116	124	123	1600	35	30	28
3100	208	220	219	1500	16	14	13
3000	378	393	380				

Table B-XV

Two Clamp On Transducers Correlation
Span = 50 in.

Pump Speed (RPM)	Pressure (PSI)			Pump Speed (RPM)	Pressure (PSI)		
	In-Line	Clamp-On A	Clamp-On B		In-Line	Clamp-On A	Clamp-On B
4500	92	175	178	2900	153	143	132
4400	148	243	231	2800	74	64	56
4300	134	196	176	2700	50	38	30
4200	132	181	160	2600	43	32	31
4100	184	250	211	2500	52	99	118
4000	302	531	417	2400	52	87	97
3900	307	477	329	2300	54	93	101
3800	107	64	54	2200	65	61	59
3700	54	36	21	2100	129	134	132
3600	34	30	38	2000	192	197	192
3500	91	131	163	1900	106	107	100
3400	116	133	150	1800	58	54	51
3300	95	105	106	1700	40	33	31
3200	111	117	118	1600	35	26	25
3100	194	197	196	1500	16	22	16
3000	379	375	360				

APPENDIX C

HSFR - Input Data and Output Plots

HYDRAULIC SYSTEM FREQUENCY RESPONSE PROGRAM

CONFIGURATION-STRAIGHT LINE PUMP TO RLS FREQUENCY RESPONSE

RESPONSE IS CALCULATED FROM 50.00 TO 5000.00 R.P.M. IN INCREMENTS OF 50.00 R.P.M.

RESPONSE IS PLOTTED FOR THE -FIRST- HARMONIC FREQUENCY

NUMBER OF PUMPING ELEMENTS= 9.

FLUID DATA FOR MIL-H-5606 AT 3000.0 PSIG AND 130.0 DEG F

VISCOSITY = .294E-01 IN**2/SEC
DENSITY = .521E-04 (LB-SEC**2)/IN**4
BULK MODULUS = .244E+05 PSI

ELEMENT NUMBER	M TYPE	F TYPE	SYSTEM ELEMENT INPUT DATA — PHYSICAL DATA							
1	9	21	.117	.559	1.075	1.894	.532	.260	.101	
			.13300	20.60000	3.05000	2.12095	26.70000	21.30000	25.70000	16.00000
			50.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
2	1	1	50.000	.250	0.000	68517.000	0.000	0.000	0.000	
3	1	0	7.125	.125	.065	30000000.000	0.000	0.000	0.000	
4	3	0	.164	0.300	0.030	0.000	0.000	0.000	0.000	
5	1	0	14.225	.125	.065	30000000.000	0.000	0.000	0.000	
6	1	0	10.000	.125	.065	30000000.000	0.000	0.000	0.000	
7	1	0	10.000	.125	.065	30000000.000	0.000	0.000	0.000	
8	1	0	10.000	.125	.065	30000000.000	0.000	0.000	0.000	
9	1	0	10.000	.125	.065	30000000.000	0.000	0.000	0.000	
10	1	0	10.000	.125	.065	30000000.000	0.000	0.000	0.000	
11	1	0	10.000	.125	.065	30000000.000	0.000	0.000	0.000	
12	1	0	10.000	.125	.065	30000000.000	0.000	0.000	0.000	
13	1	0	10.000	.125	.065	30000000.000	0.000	0.000	0.000	
14	1	0	10.000	.125	.065	30000000.000	0.000	0.000	0.000	
15	1	0	10.000	.125	.065	30000000.000	0.000	0.000	0.000	
16	1	0	11.200	.125	.065	30000000.000	0.000	0.000	0.000	
17	3	0	.134	0.600	0.030	0.000	0.000	0.000	0.000	
18	1	0	14.475	.125	.065	30000000.000	0.000	0.000	0.000	
19	1	0	10.000	.125	.065	30000000.000	0.000	0.000	0.000	
20	1	0	10.000	.125	.065	30000000.000	0.000	0.000	0.000	
21	1	0	10.000	.125	.065	30000000.000	0.000	0.000	0.000	
22	1	0	10.000	.125	.065	30000000.000	0.000	0.000	0.000	
23	1	0	10.000	.125	.065	30000000.000	0.000	0.000	0.000	
24	1	0	10.000	.125	.065	30000000.000	0.000	0.000	0.000	
25	1	0	10.000	.125	.065	30000000.000	0.000	0.000	0.000	
26	1	0	10.000	.125	.065	30000000.000	0.000	0.000	0.000	
27	1	0	10.000	.125	.065	30000000.000	0.000	0.000	0.000	
28	1	0	10.000	.125	.065	30000000.000	0.000	0.000	0.000	
29	1	0	10.000	.125	.065	30000000.000	0.000	0.000	0.000	
30	1	0	10.000	.125	.065	30000000.000	0.000	0.000	0.000	
31	1	0	10.000	.125	.065	30000000.000	0.000	0.000	0.000	
32	3	0	.164	0.300	0.000	0.000	0.000	0.000	0.000	
33	1	0	14.475	.125	.065	30000000.000	0.000	0.000	0.000	
34	5	0	1.500	0.000	0.000	0.000	0.000	0.000	0.000	
35	6	1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	
36	11	0	0.000	.250	.071	30000000.000	0.000	0.000	0.000	
37	1	9	0.275	.125	.065	30000000.000	0.000	0.000	0.000	
38	14	0	1532.500	3.000	0.000	0.000	0.000	0.000	0.000	

Figure. C-1. Input Data for the System with Hose

HYDRAULIC SYSTEM FREQUENCY RESPONSE PROGRAM

CONFIGURATION-STRAIGHT LINE PUMP TO RLS FREQUENCY RESPONSE

RESPONSE IS CALCULATED FROM 50.00 TO 5000.00 R.P.M. IN INCREMENTS OF 50.00 R.P.M.

RESPONSE IS PLOTTED FOR THE -FIRST- HARMONIC FREQUENCY

NUMBER OF PUMPING ELEMENTS= 9.

FLUID DATA FOR MIL-H-5606B AT 3000.0 PSIG AND 100.0 DEG F

VISCOSITY = .2446E-01 IN**2/SEC
DENSITY = .8215E-04 (LB-SEC**2)/IN**4
BULK MODULUS = .2446E+06 PSI

ELEMENT NUMBER ************ SYSTEM ELEMENT INPUT DATA ************

ELEMENT NUMBER	M TYPE	K TYPE	....	....	....	PHYSICAL DATA	....	....	....	....
1	9	21	.117	.552	1.096	1.096	.552	.263	.131	
			.13300	20.00000	3.00000	2.62000	25.20000	21.90000	25.70000	[illegible]
			72.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
2	1	9	41.000	.625	.065	30000000.000	0.000	0.000	0.000	
3	1	0	2.375	.625	.065	30000000.000	0.000	0.000	0.000	
4	3	0	.104	3.000	0.030	6.295	0.000	0.000	0.000	
5	1	0	14.325	.625	.065	30000000.000	0.000	0.000	0.000	
6	1	0	10.000	.625	.065	30000000.000	0.000	0.000	0.000	
7	1	0	10.000	.625	.065	30000000.000	0.000	0.000	0.000	
8	1	0	10.000	.625	.065	30000000.000	0.000	0.000	0.000	
9	1	0	10.000	.625	.065	30000000.000	0.000	0.000	0.000	
10	1	0	10.000	.625	.065	30000000.000	0.000	0.000	0.000	
11	1	0	10.000	.625	.065	30000000.000	0.000	0.000	0.000	
12	1	0	10.000	.625	.065	30000000.000	0.000	0.000	0.000	
13	1	0	10.000	.625	.065	30000000.000	0.000	0.000	0.000	
14	1	0	10.000	.625	.065	30000000.000	0.000	0.000	0.000	
15	1	0	10.000	.625	.065	30000000.000	0.000	0.000	0.000	
16	1	0	10.000	.625	.065	30000000.000	0.000	0.000	0.000	
17	3	9	.104	3.000	0.030	0.000	0.000	0.000	0.000	
18	1	0	14.575	.625	.065	30000000.000	0.000	0.000	0.000	
19	1	0	10.000	.625	.065	30000000.000	0.000	0.000	0.000	
20	1	0	10.000	.625	.065	30000000.000	0.000	0.000	0.000	
21	1	0	10.000	.625	.065	30000000.000	0.000	0.000	0.000	
22	1	0	10.000	.625	.065	30000000.000	0.000	0.000	0.000	
23	1	9	10.000	.625	.065	30000000.000	0.000	0.000	0.000	
24	1	0	10.000	.625	.065	30000000.000	0.000	0.000	0.000	
25	1	0	10.000	.625	.065	30000000.000	0.000	0.000	0.000	
26	1	0	10.000	.625	.065	30000000.000	0.000	0.000	0.000	
27	1	0	10.000	.625	.065	30000000.000	0.000	0.000	0.000	
28	1	9	10.000	.625	.065	30000000.000	0.000	0.000	0.000	
29	1	0	10.000	.625	.065	30000000.000	0.000	0.000	0.000	
30	1	0	10.000	.625	.065	30000000.000	0.000	0.000	0.000	
31	1	0	10.000	.625	.065	30000000.000	0.000	0.000	0.000	
32	9	0	.104	7.000	0.003	0.009	0.000	0.000	0.000	
33	1	0	14.625	.625	.065	30000000.000	0.000	0.000	0.000	
34	9	0	1.500	0.000	0.030	0.000	0.000	0.000	0.000	
35	6	1	0.400	1.039	0.030	0.000	0.000	0.000	0.000	
36	11	0	7.500	.259	.031	30000000.000	0.000	0.000	0.000	
37	1	0	7.377	.625	.051	30000000.000	0.000	0.000	0.000	
38	14	0	1537.500	5.039	0.035	0.000	0.000	0.000	0.000	

Figure. C-2. Input Data for the System with Tube

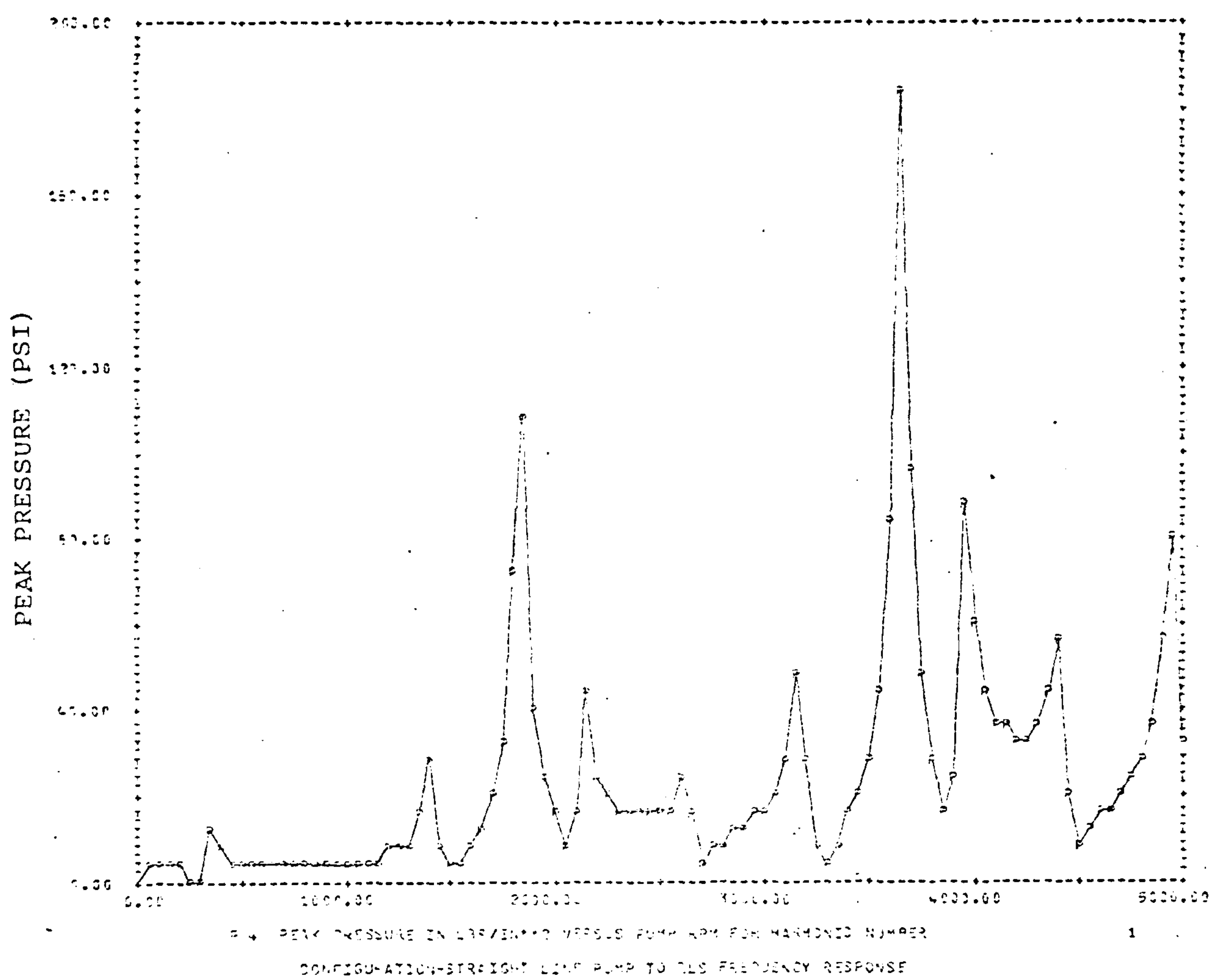

Figure. C-3. System with Hose
Transducers 43 in. from Pump

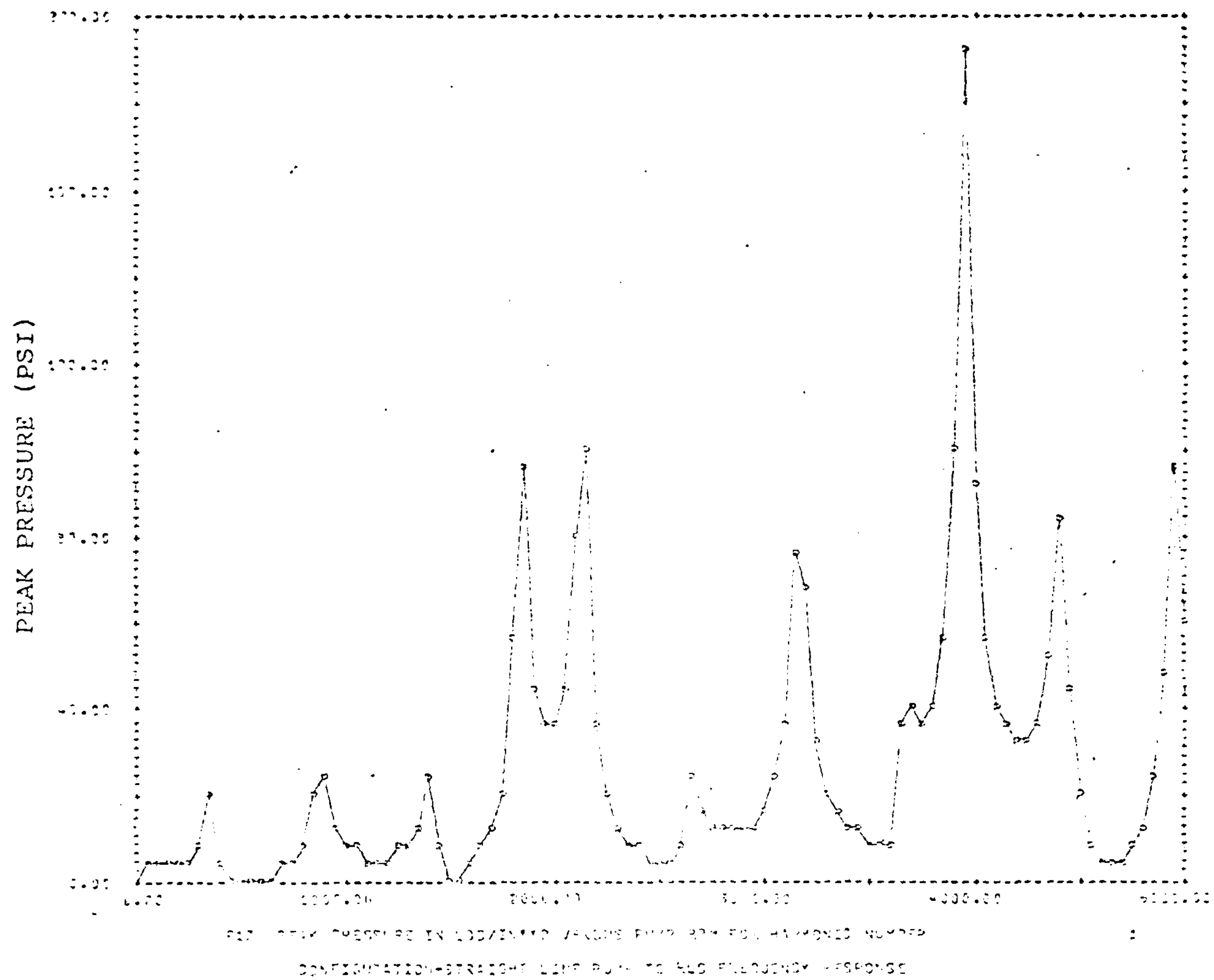

Figure. C-4. System with Hose
Transducers 169 in. from Pump

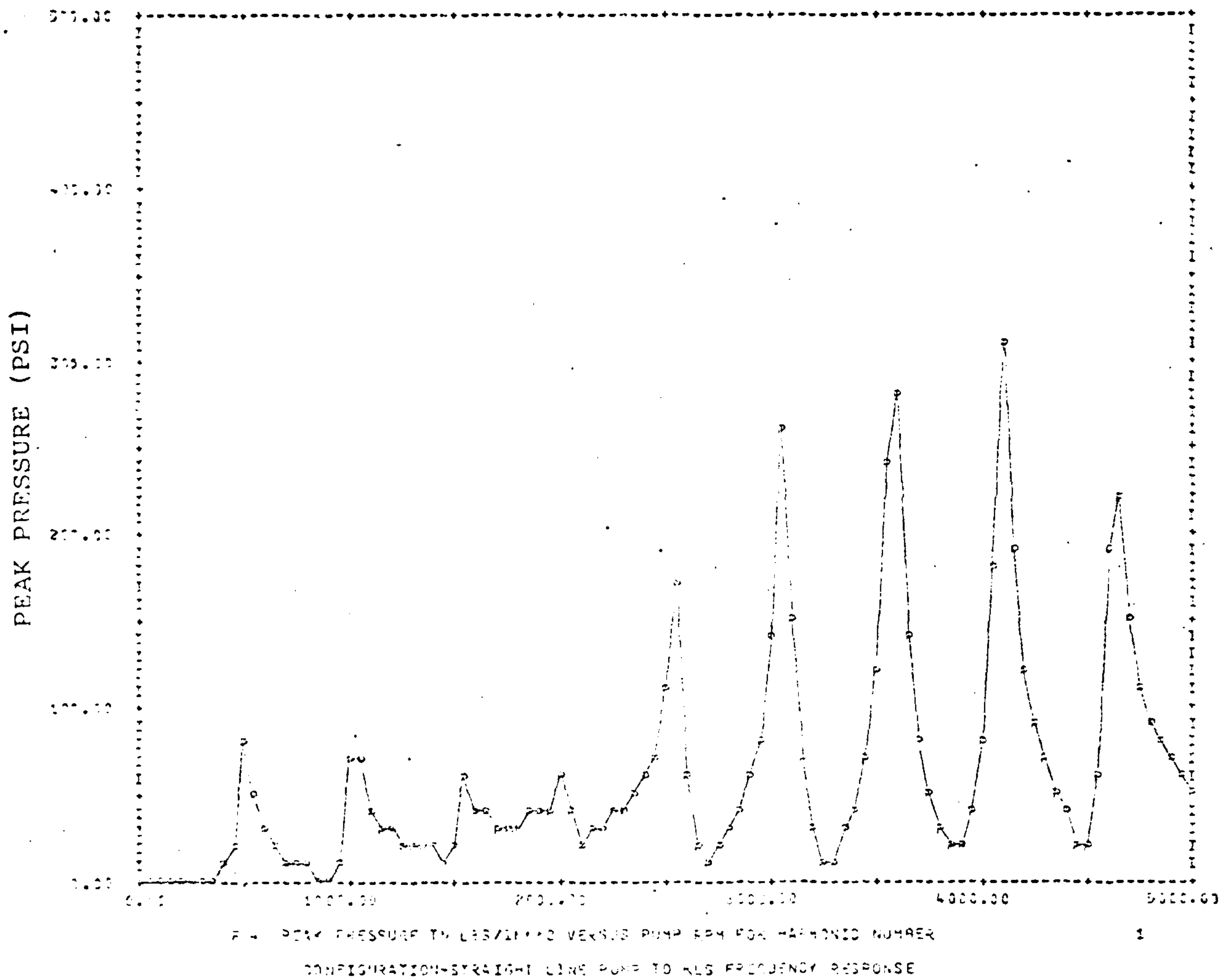

Figure. C-5. System with Tube
Transducers 43 in. from Pump

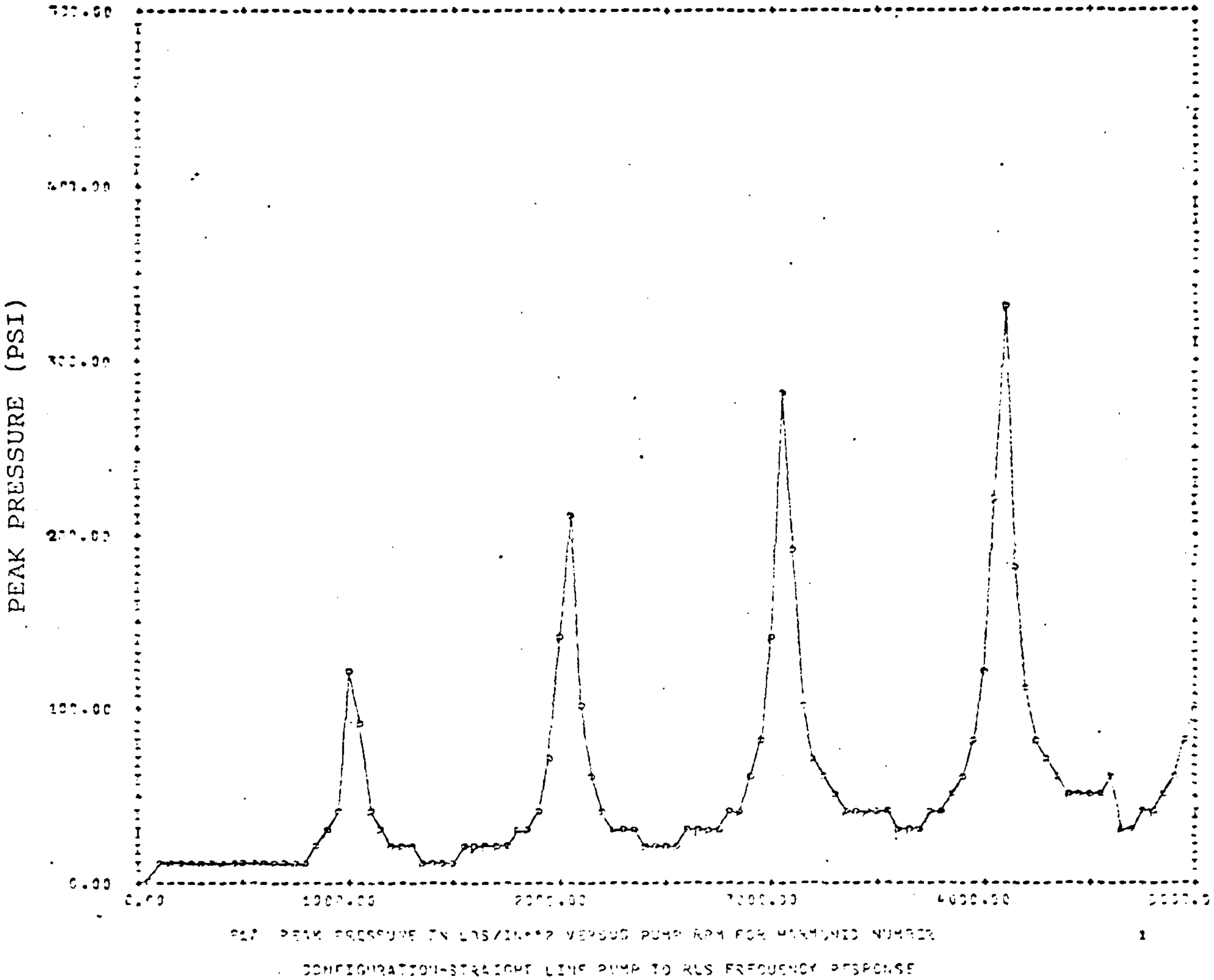

Figure. C-6 System with Tube
Transducers 169 in. from pump

APPENDIX D

Clamp-on Transducer Clamps

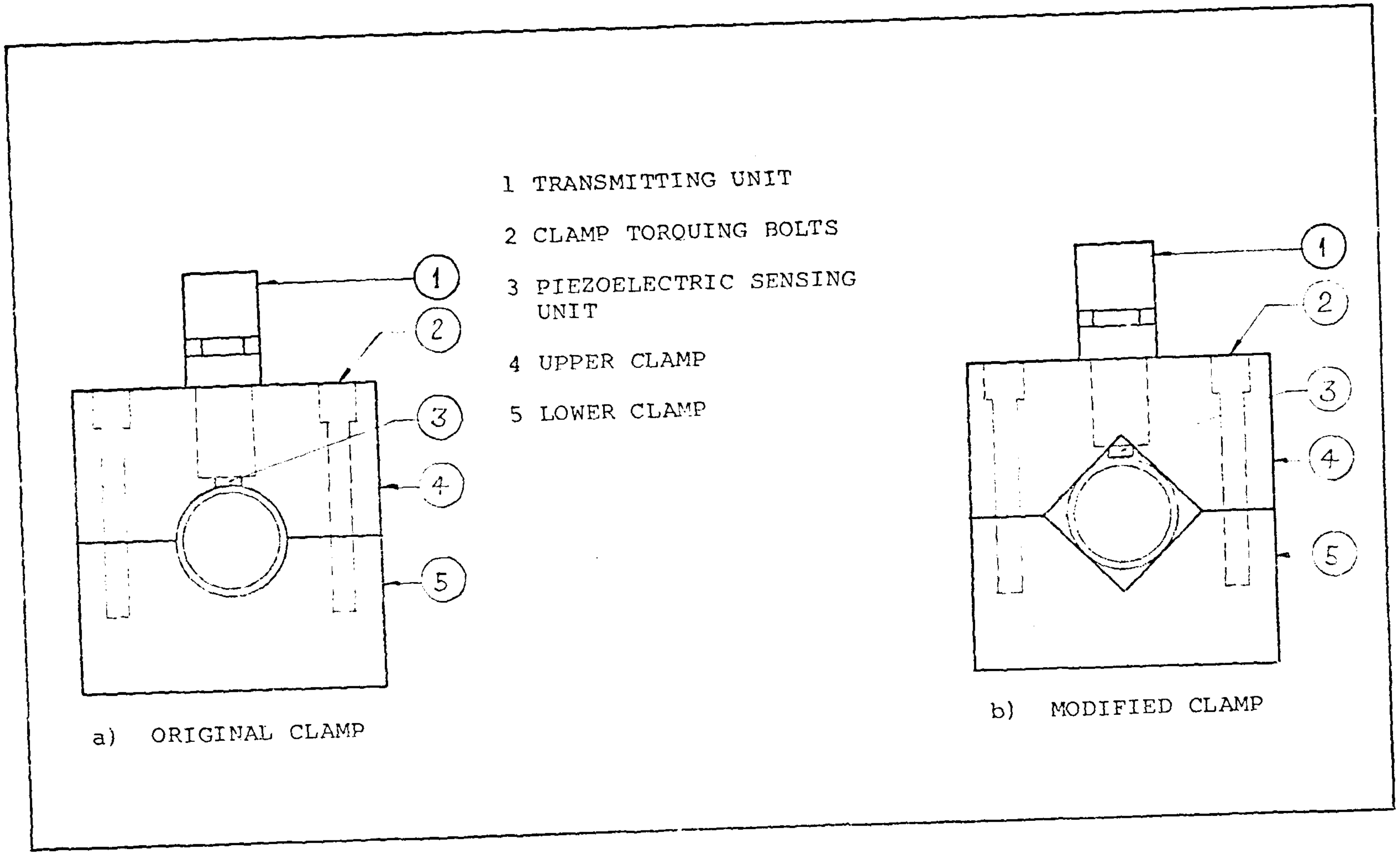

Figure. D-1. Clamp-on Transducer Clamps

VITA

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This study is concerned with two basic techniques for measuring oscillatory and transient hydraulic pressures: use of a standard fluid line transducer (in-line) and a transducer clamped to the outside of the line (clamp-on).

Both transducers were installed in a laboratory hydraulic system side by side. Several sets of runs were made under various conditions. Measurements taken indicated deviations between the [illegible] as high as 1 20%. The clamp-on transducer w[illegible]

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affected by the line vibrations and should be used in a hydraulic system with some limitations.

The experimental measurements were compared with the theoretical results from a frequency response computer program. The measured oscillatory pressures were up to 30% greater than those predicted by the computer program.